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A SMALL-WATERPLANE-AREA-SINGLE-HULL SHIP WITH STABILIZING HYDROFOILS (SWASH): SEAKEEPING CHARACTERISTICS AND CALM WATER PERFORMANCE

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It is found that in random waves SWASH undergoes less severe motions than the conventional monohull, and is comparable (slightly worse in pitch, generally better in heave) to a recent SWATH design. EHP for SWASH and SWATH are determined to be roughly the same, and appreciably higher than that for the conventional monohull in the speed range 25.5 knots to 32.0 knots.

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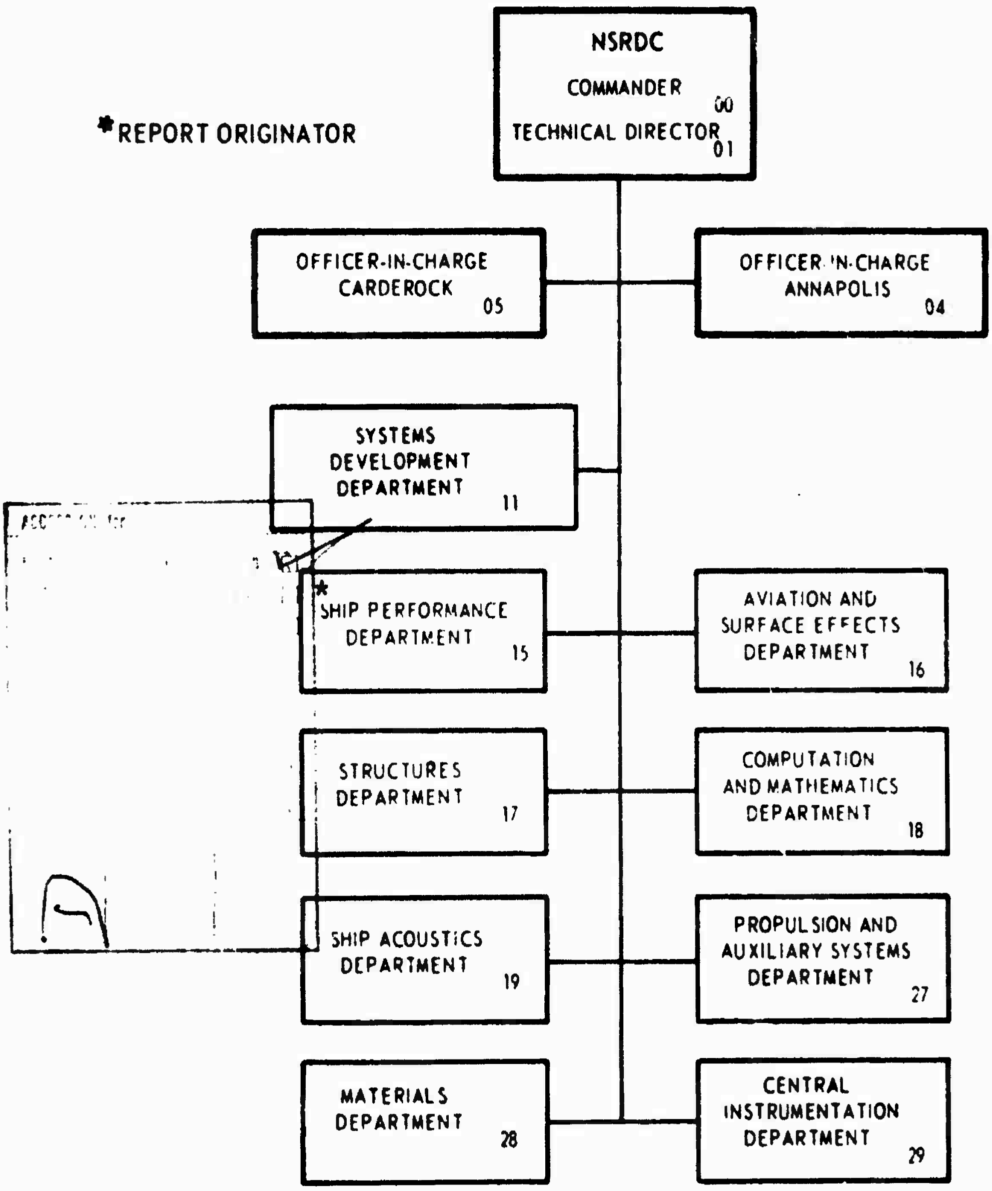

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ABSTRACT

Stability, seakeeping and resistance characterization experiments have been conducted on a novel ship (SWASH) which incorporates a single, small waterplane area hull and outrigger surface piercing hydrofoils for stability. Comparisons are provided between pitch and heave transfer functions for SWASH and those of a small waterplane area twin hull (SWATH) and a conventional monohull. Root-mean-square motions in head Sea States 5 and 6 are also compared for these vessels, as well as effective horsepower (EHP) in calm water. It is found that in random waves SWASH undergoes less severe motions than the conventional monohull, and is comparable (slightly worse in pitch, generally better in heave) to a recent SWATH design. EHP for SWASH and SWATH are determined to be roughly the same, and appreciably higher than that for the conventional monohull in the speed range 25.5 knots to 32.0 knots.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

In recent years much research effort has been expended in the development of small waterplane area twin hull (SWATH) ships. These vessels provide large deck area, and appear to have good seaworthiness characteristics in head seas. The marriage of a single waterplane area hull and outrigger hydrofoils was conceived at the Naval Ship Research and Development Center as an alternate method of providing much open topside area and good seakeeping performance. In this concept, the hydrofoil units would be supported under a deck which is extended transversely from the main hull. It was believed that SWASH (The acronym used for the single hull-foil combination) offered the potential for lower power requirements and smaller structural weight fraction than SWATH. In order to determine the resistance of a first-cut version of SWASH, and to characterize its motions in a seaway, the experiments documented in this reports were carried out.

DESCRIPTION OF MODEL AND TEST EQUIPMENT

MODEL

The SWASH model is a composite of a small waterplane area hull, four surface-piercing foil units, and four planing floats assembled as shown in Figure 1. The upper deck structure was not modeled because of space limitations. Lines for the submerged portion of the main hull are given in Figure 2, and the body plan for the planing floats is presented in Figure 3. The lower body of the mainhull has circular sections; the undulation in outer contour along its length is incorporated to minimize wavemaking resistance. The floats have a variation in deadrise forward of the midsection (Station 5) and have a prismatic form from Station 5 aft.

Particulars of the model as tested, and of the ship it represents are given in Table 1. The deck beam tabulated is nominal, and depends in part on the lateral distance between the foil units. This is, of course, dependent upon the stability requirements and foil configuration. The lateral foil spacing was larger than desired during these experiments because ballasting difficulties resulted in a larger value of model $\overline{KG}$ than the 1.38 ft specified by the designers. The resulting reduction in roll stability was, therefore, compensated for by increasing the lateral separation of the foil units.

The foils were fabricated from aluminum using a 10 percent thick NACA 64A010 section. Camber was introduced by using an NACA a = 1.0 mean line adjusted for a section lift coefficient of 0.45. A sketch of the foil section is provided in Figure 4. The foil chord is 5.5 inches (9.4 ft full scale).

As shown in Figure 5, two vee form foils having the section of Figure 4 were assembled in a ladder arrangement with supporting struts. Because of the desire to vary relative angle of attack and spacing between the upper and lower foils during these experiments. The struts are slotted and therefore not "clean". The dihedral angle of the lower foil is 40 degrees and that of the upper foil is 30 degrees, while the slant lengths of the lower and upper foils are 23.2 inches (39.4 ft full scale) and 14.2 inches (24.1 ft full scale) respectively. The span of the foil unit--that is, the horizontal distance from tip to tip on the lower foil--is 37.6 inches (63.9 ft full scale).

The upper surface of the foils was slotted to permit installation of fences to inhibit lateral air inflow and flow ventilation on the suction side of the foil. Guidance was obtained from Reference 1 for the design of these fences which are shown mounted on the foil in Figure 4. Early experiments revealed that by mounting fences only in the most outboard slots on the upper foil, it was generally possible to prevent ventilation inboard of the fences. Further, the lower foil did not require fences since it exhibited no tendency to ventilate, even at the highest speed and smallest immersion investigated. An additional measure was taken to prevent ventilation in concert with the fences: a light sprinkling of fine sand was placed on each of the foils, 10 percent of the chord aft of the leading edge. This 1/8-inch wide sand strip served to stimulate turbulence, thereby delaying laminar separation which could lead to ventilation inception.

The planing floats are used to provide stability at zero and low speeds since the foils do not develop enough lift to stabilize the vessel in those conditions. The floats have an overall length, LOA, of 46 inches, a beam, B, of 6-1/4 inches, and an overall depth, D, of 6-1/2 inches (LOA = 78.2 ft, B = 10.6 ft and D = 11.1 ft full scale).*

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1 Sottorf, W., "Experimental Investigations Concerning the Problems of Hydrofoils," (first reported in December 1940), David Taylor Model Basin Translation No. 299 (June 1966).

* Since the model had no deck structure, the float depth was made somewhat greater than would be required. Normally the float would be attached to the underside of the deck.

During the experiments with combination foil and float units attached to the main hull, the floats were usually set at a trim angle of 4 degrees. The spacing between the keel of the float at its midlength and the top of the upper foil apex was 4.1 inches (7.0 ft full scale) when both foils and float were at zero trim angle.

The longitudinal, transverse and vertical positions of the foil units on the model are adjustable, as is the foil angle of attack. Initial settings were selected to achieve the desired pitch, heave, and roll stability. Data from the first series of experiments with a single foil unit were used to guide the selection. The foils were adjusted vertically so that in undisturbed water at the design ship speed of 32 knots, the apexes of the upper foils would be just out of the water. Due to the wave disturbance from the forward foils, however, the after foils ran with somewhat greater immersion than desired.

TEST EQUIPMENT

Before carrying out experiments with the complete SWASH model, experiments were conducted with only a single hydrofoil unit (no hull). It was attached to the towing carriage in the Naval Ship Research and Development Center's Deep Basin which is 1400 ft long by 22 ft deep by 51 ft wide. The foil was supported by a strut mounted to vertical rails; this permitted the making of depth changes by actuation of a winch.

Lift and drag were measured by means of "block gages". Each gage is a cube-shaped module containing flexures and a differential reluctance sensing element. The lift gage (sensing the vertical component of total force) is rated at $\pm$ 100 lb, and the drag gage (sensing the horizontal force component) is rated at $\pm$ 25 lb. The gages were mounted between the bottom of the tow strut and the top of the foil unit assembly in much the same way as shown in Figure 1, where the gages can be seen just below the transverse support tubes.

The complete SWASH model (hull plus four foil units) was also tested in the Deep Basin in calm water and in waves. The waves were generated by a pneumatic-type wavemaker located at one end of the tank. This was electronically controlled to generate long-crested regular waves, or random waves having a preprogrammed spectral shape. The model was self-propelled and attached to two "grasshopper" arms mounted to the carriage. This arrangement permitted freedom in pitch, heave, surge, and roll. Since yaw and sway were restrained, it was not necessary to steer the model to keep it on course.

Pitch and roll were measured by means of a gyroscope housed in the main hull. An ultrasonic transducer mounted on the hull was used to obtain heave displacement and a second ultrasonic transducer mounted 14.5 ft forward of the model's center of gravity was employed for wave height measurement. Block gages were again used to measure lift and drag--this time on all four foil units. Since the model speed was essentially identical to the carriage speed, it was determined by use of a magnetic pickup and a slotted wheel which rotated with the carriage wheels.

The transducer signals were amplified and recorded on paper strip chart. They were also digitized at 10 samples/channel/sec during the course of a run, and much of the data reduction was performed on an Interdata Model 4 digital computer. Such things as average ("D.C. level") trim and heave, as well as root-mean-square and amplitude values of dynamic motions, were printed out via the computer immediately after completion of a pass down the tank. For some runs, integrating digital voltmeters were used to obtain root-mean-square values of wave height as a check on the Interdata system.

TEST PROGRAM AND PROCEDURE

HYDROFOIL UNIT

The lift and drag characteristics of a single hydrofoil unit were determined in calm water in order to provide data needed for the experiments with the complete model. In all cases, the model speeds examined were 3.76, 4.43, 5.76, and 7.08 knots which correspond to 17, 20, 26, and 32 knots full scale.

The lower foil alone (upper foil and float detached) was tested first. To determine the effect of depth of immersion on lift and drag, the foil apex was set at five distances (measured along the foil centerline)* below the free water surface, ranging from 2.0 inches to 16.0 inches (3.4 ft to 27.2 ft full scale)+. Trim angles examined range from -16 degrees to +20 degrees, in steps sufficient to define the lift and drag curves up to the stall condition.

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* This direction of measurement will be used throughout this report.

+ Δd used in plots which will be introduced later, was obtained by subtracting 8.6 inches (the distance between upper and lower foil apexes) from the immersion depth of the lower foil apex.

The assembly of lower and upper foils was also tested both with and without the float attached. In this case, lower foil trim angle ranged from -16 degrees to +16 degrees with no float, and between +2 degrees and +16 degrees with the float installed. The angle on the upper foil was either 3, 5, or 7 degrees greater (i.e., in the direction producing larger upward force) than that on the lower foil. Two spacings between foil apexes were examined, viz. 7.7 inches and 8.6 inches (13.1 ft and 14.6 ft full scale). Lower foil immersion ranged from 10.1 inches to 14.6 inches (17.2 ft to 24.8 ft full scale) when the float was not in place, and from 10.1 inches to 16.0 inches (17.2 ft to 27.2 ft full scale) with the float installed. The keel of the float was positioned 4.1 inches (7.0 ft full scale) above the high point of the upper foil apex when both were at zero degree trim. Float trim angles ranging from 4 degrees bow down to 6 degrees bow up were examined. After the initial experiments revealed that the upper foil was ventilating, two fences having the dimensions shown in Figure 4, were placed in the furthest outboard slot locations on the upper foil. The starboard slots can be seen in Figure 5. Ventilation was then frequently confined to the region outboard of the fences.

The last experiments examined the lift and drag characteristics of the float alone. Float draft at midships ranged from 0.5 inches to 4.0 inches (0.9 ft to 6.8 ft full scale) and trim angles of 0, $\pm$ 2, $\pm$ 4, and +6 degrees were investigated.

COMPLETE SWASH MODEL

Initial experiments with the SWASH model were performed in calm water. During these tests the foils, floats and ballast weights* were adjusted in order to minimze trim and heel when underway at the two speeds investigated--5.65 knots and 7.08 knots+ (25.5 knots and 32.0 knots full scale). Although during pretest setup all foil units were adjusted to trim angles of 6 degrees on the lower foil, 11 degrees on the upper foil and 4 degrees on the float, the settings established by the end of the calm water experiments in order to level the model are as shown in the table below.

FOIL UNIT	LOWER FOIL	UPPER FOIL	FLOAT
FORWARD PORT	7 deg	12 deg	5 deg
FORWARD STARBOARD	6	11	4
AFT PORT	10	15	8
AFT STARBOARD	9	14	7

It can be seen that the after foils were set at larger angles than the forward ones; this was necessary in large part because of the downwash and surface waves caused by the forward foils. Furthermore, angles on the port foils were larger than those on the starboard side because, for

* A motorized, transverse weight shifter can be seen in Figure 1 above the model number on the strut. The longitudinal weight shifter was located in the main hull.

+ These speeds were also run for the wave tests.

some unspecifiable reason--perhaps a slight yaw angle on the foils or other foil asymmetry--the model tended to roll to port. For all but one run, the foil units were positioned vertically with the upper foil apex 22.4 inches (38.1 ft full scale) above the main hull keel. Since 38 ft is the keel draft at 32 knots, the upper foil apex was just above the water surface when the ship was underway in undisturbed water. One run was made at 5.6 knots (25.5 knots full scale) with the after foils lowered 3 inches to determine the effect on trim. It was changed from about 1.5 degrees bow up to 1.0 degree bow down. This had the effect of reducing the foil loading, and increasing the natural periods and foil submergence. However, there was not sufficient time available to determine how this altered the motions in waves.

In order to obtain pitch and heave response amplitude operators (PAO's), experiments were carried out in head regular waves. Wavelength to ship length ratios of 2.0, 3.0, 4.0, 5.0, and 6.0 were investigated. Wave heights were kept low to minimize nonlinear vessel responses. Thus, for all wavelengths, the wave heights fell in the 2.5 inch to 3.5 inch range (4.3 ft to 6.0 ft full scale); this gave a wave steepness (wave height/wavelength) range of 1/500 to 1/100.

Performance of the SWASH in the long-crested, random, head seas was determined by conducting tests in the scaled down seaways listed below.

SEA STATE	SIGNIFICANT WAVE HEIGHT		FREQUENCY OF MAXIMUM ENERGY	
	MODEL SCALE, IN.	FULL SCALE, FT.	MODEL SCALE, cps	FULL SCALE, cps
3	2.9	4.9	0.68	0.15
5	5.2 - 6.6	8.9 - 11.3	0.49	0.11
6	7.8	13.3	0.49	0.11

Tests in Sea State 3 were run at the 25.5 knots full scale speed only, whereas in the other two sea states speeds of both 25.5 and 32.0 knots were investigated.

To inhibit foil ventilation, fences were installed on all four upper foils in the second most outboard slot location shown in Figure 5. They were used for both calm water and wave tests.

EXPERIMENTAL RESULTS

MOTIONS IN REGULAR WAVES

Pitch and heave transfer functions for operation in head, regular waves are presented in Figures 6 through 9, where comparisons are made between SWASH, several SWATH forms, and a new, "conventional" destroyer (monohull). All data are full scale. The comparisons are made on the basis of equal ship length since this design variable has a pronounced effect on ship motions in head seas. Principal characteristics of the SWATH ships and monohull are given in Table 2 along with a sketch indicating major differences in shape. Low aspect ratio fins were attached to the lower hull of SWATH IV at station 18 to provide improved stabilization. Experiments were conducted with two different size fins. The large fins have a full scale chord of 13.6 ft and a span of 16.4 ft. The small fins have the same chord as the large ones, but a span of only 11.3 ft. Also blisters, for increased damping, were attached to the port and starboard sides of the hull strut and extended longitudinally from the forward end of the strut to the forward end of the rudder. They were 11 ft deep and, when installed, doubled the thickness of the underlying strut. The motions data for the SWATH I, SWATH II and SWATH IV were obtained from Reference 2 and from the results of other experiments conducted at the Naval Ship Research and Development Center.

In Figure 6, it can be seen that the maximum pitch response for SWASH at 25.5 knots is about the same as that of SWATH IV with blisters at 20.6 knots. This maximum occurs at a wavelength/ship length, λ/L, of 3.5 to 4.0. Since SWATH IV with blisters is somewhat more sharply tuned than SWASH, it pitches less in waves longer and shorter than approximately 3.5 times the ship length. SWATH IV with large fins appears to be very sharply tuned (there were not sufficient data available to define the complete curve). This fact, coupled with the occurrence of the maximum response at $\lambda/L = 5.3$ (this corresponds to a wavelength of 1,620 feet, which is infrequently encountered in seas below State 6 in severity) indicates that SWATH IV when fitted with large fins will generally have good pitch characteristics in the open ocean. SWATH I at 20.7 knots has approximately the same maximum pitch response as SWASH and also has a broad transfer function. However, the fact that its maximum pitch occurs in an even longer (and less common) wave, may give

[2] Jones, H.D., Gerzina, D.M., "Motions and Hull-Induced Bridging Structure Loads for a Small Waterplane Area, Twin-Hull Attack Aircraft Carrier in Waves," (SWATH II), Naval Ship Research and Development Center Report 3819 (August 1973).

it a slight advantage over SWASH when operating in a seaway. SWATH II at 18.0 knots, with its oblate hull sections which contribute to damping, has the most favorable pitch transfer function. It has low values of pitch per unit wave slope at those wavelengths which predominate in the open ocean. The conventional monohull at 18.3 knots has a peak pitch response which is about 1.5 times that of SWASH and its resonance occurs at a wavelength of about 520 feet which is prevalent at sea. It clearly has the worst pitching characteristics. In summary, it can be stated that for head sea operation at the speeds specified in Figure 6, SWATH II performs best in pitch, the conventional monohull has the worst performance, and SWASH, SWATH IV, and SWATH I have comparable pitch characteristics of intermediate quality.

The heaving response of SWATH I and SWATH IV in head waves is much worse than that of SWASH and SWATH II (see Figure 7). The maximum heave per unit wave amplitude for SWATHS I and IV is approximately 3.0; this is twice that for SWASH. For SWATH I in particular, the large peak value is undesirable because it occurs at a wavelength commonly encountered in the open ocean. In contrast, it would be necessary for SWASH to operate in a State 7 sea or higher to find significant wave energy at critical wavelengths. Although the conventional monohull has the lowest magnification of 1.2 at resonance ($\lambda/L = 1.1$), it will be excited at its natural frequency more frequently than the other ships when operating in a seaway.

At speeds of 32.0 knots and 33.0 knots, respectively for SWASH and SWATH IV, the SWASH ship has a much less favorable pitch transfer function that the twin hull vessel. Figure 8 shows that SWASH reaches a maximum unit pitch response of 2.1 whereas that for SWATH IV with large fins does not exceed 1.1.

In Figure 9 it can be seen that heaving response for SWASH and SWATH IV, with blisters and small fins is comparable when they are operating in head waves at 32.0 knots and 33.0 knots, respectively. The curve for SWATH IV with large fins falls below the other curves up to $\lambda/L = 4.8$. This leads one to conjecture that it will experience less heave in all but very severe seaways. However, it should be remembered that the natural pitch and heave periods for SWASH can be increased by reducing the foil loading.

MOTIONS IN RANDOM WAVES

Experimental motions results for operation in head, random seas are presented in Figure 10 through 15. Comparisons of root-mean-square (RMS) pitch and heave for SWASH, SWATH II, SWATH IV with large fins, and the conventional monohull are made. All ships are compared on the basis of equal length (306 ft). In addition, a curve for the conventional monohull with displacement equal to that of SWASH is also shown.

In Figures 10 and 11 which show RMS pitch as a function of speed in Sea States 5 and 6 respectively, it is obvious that the conventional monohull pitches most severely. There is substantially better performance from the 433 foot long conventional monohull having the same displacement as SWASH than there is from the 306 foot long version. However, even the larger monohull does not compare favorable with the other ship types. Further, the two monohulls are, as shown, operating at lower speed than the SWASH and SWATH IV forms. SWASH exhibits greater pitch response than SWATH IV with large fins in both seas states, particularly at the higher speed of 32.0 knots. This bears out the conclusions reached previously on the basis of the transfer functions (see Figure 7 and discussion for example). SWATH II at 9 knots has about the same RMS pitch as SWASH at 32 knots.

RMS heave is given in Figures 12 and 13. In Sea State 5 the conventional monohull exhibits the largest motion for its higher speeds of operation. However, in Sea State 6 SWATH IV appears to have the worst heaving characteristics. With the exception of the 32 knots speed in Sea State 5, the SWASH performs best in heave. The reversal in superiority between SWASH and SWATH IV at the highest speed in Sea States 5 and 6 could be due to the fact that the portion of the wavemaker control program used for the Sea State 5 run contained more short waves than the segment used for Sea State 6. As shown in Figure 9, SWASH would respond more to relatively short waves than would SWATH IV with large fins.

When a theoretical method of calculating ship motions is being developed it is important to know how linearly the responses vary with wave height. Figures 14 and 15 give an approximate indication of this. It can be seen that up to an RMS wave height of 3.3 feet (which corresponds to a Sea State 6) the pitch and heave motions--particularly the latter--appear to be fairly linear. Some frequency effect is, however, intermixed with the wave height effect, since for the lowest wave height there were more short waves encountered by the model than there were for the two higher wave heights. Thus, the proximity of the wave encounter frequency to resonance is different for different wave heights.

CALM WATER EXPERIMENTS

Hydrofoil Unit Lift and Drag

Examples of curves prepared to characterize the lift and drag of a single hydrofoil unit are given in Figures 16 through 21. These and similar curves were used when selecting initial foil settings for tests of the complete SWASH model.

Figures 16 and 17 were cross-plotted from curves faired through measured data points. Since the ordinate (lift divided by dynamic pressure, L/q) exhibited a reasonably small speed dependence, a single curve was faired through the data points. The largest deviation from the faired curve generally occurred for the lowest speed of 17 knots full scale.

Although the fences did appear to inhibit ventilation of the upper foil, they did not have a marked effect on lift. This is shown in Figure 18 where only for trim angles of 4 degrees/7 degrees (lower foil/upper foil) is there a discernible, but small, difference in lift with and without fences.

Typical plots of drag coefficient can be seen in Figure 19 and 20. The coefficient C_D is defined as Drag/1/2 $\rho V^2 S$ with ρ being the water density, V the forward speed, and S the projected area of the immersed portion of the foils. The data points shown in Figure 19 for given values of Δd and foil trim angle are for the four speeds investigated; this indicates how division of drag by speed-squared caused the data to collapse.

Lift-to-drag ratio, L/D, at a full scale speed of 32 knots is plotted as a function of foil immersion in Figure 21. The very close superposition of data for different foil trim angles indicates that within the range of angles investigated, this parameter has a negligible effect on L/D. The maximum value of L/D is approximately 8.0 and occurs at $\Delta d = 0$ (this was obtained without the upper foil installed). Unfortunately, when the complete foil system was tested with the hull, maximum L/D was appreciably lower--in the 4.0 to 5.0 range. It is belived that other foil configurations could be developed for SWASH which would yield more favorable lift-to-drag ratios.

Damping and Natural Periods

Time-histories obtained from free oscillation tests in calm water are presented in Figure 22. The initial peak in the traces (down for all but roll) shows how far the model was depressed prior to release. As may be seen, all of the motions were heavily damped. The largest amount of oscillation--about one cycle--occurred during the free oscillation in heave at 25.5 knots. There were never enough oscillations to yield data for a log decrement plot, or for accurately determining natural periods.

The natural periods listed in Table 1 had to be obtained by forced oscillation experiments. Since heave and pitch were strongly coupled, and the model tended to heave more than pitch, it was not possible to obtain even an approximate measure of the pitch natural period by this technique. In addition, the model ran with a bow up trim of between 1 and 2 degrees. This produced an increase loading on the foils, thereby resulting in some reduction in the natural periods. The reduced periods probably caused the model to have a less favorable frequency response during the experiments in waves, and lead to greater pitch and heave motions than would be characteristic of a more compliant SWASH ship.

Effective Horsepower

The total effective horsepower (EHP) for the SWASH ship in calm water is compared with that of SWATH IV (no appendages) and the conventional monohull in Figure 23. Data for SWATH IV were obtained from experiments performed at the Naval Ship Research and Development Center, and the total EHP for SWASH was obtained by combining data for the hull without hydrofoils with the predicted EHP for the foils only. The latter values were calculated using foil drag data obtained from the present experiments with the complete SWASH configuration, during which the model was self-propelled. This approach was necessary since resistance tests of SWASH (i.e. hull plus foils) have not been conducted.

The draft for the SWASH model at speeds corresponding to full scale values of 25.5 and 32.0 knots is known from the towing tank tests with the model free to trim and heave. These underway drafts were found to be within 2 percent of those investigated during resistance tests with the completely captive hull without foils. In addition, measurements show that in calm water the SWASH model trimmed approximately 1 degree and 2 degrees bow up, respectively, at speeds corresponding to 25.5 and 32.0 knots. A comparison of EHP predictions for the captive SWASH hull without hydrofoils at even keel and at 2.4 degrees bow up trim indicates that the EHP differed by less than 2 percent at ship speeds above 24 knots. In light of the small difference in draft between the experiments conducted on SWASH (free to trim and heave) and those carried out with the hull only (captive), and the minor changes in EHP found to occur for small change in trim, the EHP for the SWASH hull was estimated from resistance measurements made during the captive model tests.

The I.T.T.C. Friction Formulation and a correlation allowance, C_A, of 0.0004 were used in predicting full scale EHP for the hull. For the hydrofoils, measured drag was expanded to full scale EHP utilizing the chord length as the effective length, and a wetted surface corresponding to the projected area of the submerged foil surface. Foil immersion when underway was calculated from known zero speed immersion and measured changes in model trim and rise at forward speed. Both the model scale and full scale hydrofoil frictional resistance coefficients, C_f, were multiplied by a form factor of 1.12 to allow for foil shape (i.e., thickness and camber). A correlation allowance was not used because it was decided that the sand strips mounted on the foils already added sufficient roughness. Since the Reynolds number for the full scale ship is significantly higher than that on the model, flow separation, and possibly foil ventilatiion, as they are influenced by viscous effects, could be different on the prototype than they were during the model experiments. The foils selected for the SWASH ship should not cavitate at a full scale speed of 32 knots except in severe seas. However, if cavitation does occur, this may increase the drag of the foils above the fully-wetted value obtained from the model tests.

In Figure 23, it can be seen that the estimated EHP for SWASH and SWATH IV are about the same, and both of these are significantly higher than that of the conventional monohull of the same displacement. The small difference between SWASH and SWATH IV should not be given serious attention because the values for SWASH are not precise. The reasons for this are:

1. The interaction effect of the foils on the hull resistance is not taken into account.
2. There are uncertainties in the scaling procedure (e.g., form factor) used to expand the hydrofoil resistance data.
3. There is some error (albeit small) in the hull resistance because of changes in trim and draft.

CONCLUSIONS

Model experiments have been conducted on a first generation SWASH ship which combines a single, small waterplane area hull and stabilizing hydrofoils. The vessel appears to have head sea pitch characteristics that are significantly better than a conventional monohull and slightly inferior to those of the SWATH IV. Heave motion for SWASH is also clearly less severe than that of the conventional monohull--in large part because SWASH has a long natural period which would not be frequently excited by waves at sea. Further, SWASH generally compares favorably in heave with the SWATH IV. An approximate estimate of effective horsepower for SWASH yields values which are comparable to EHP for SWATH IV. Both of these ships require more propulsive power than the conventional monohull of the same displacement.

ACKNOWLEDGMENTS

The SWASH concept was conceived at the Naval Ship Research and Development Center, and was developed by Dr. P. Pien and Dr. M. Martin who performed most of the analyses leading up to the present design. Thanks are due Messrs. M.J. Davis and S. McGuigan for writing the data reduction programs used in this investigation and for their assistance in conducting the model experiments. The author also wishes to thank Mr. T.M. Pemberton for his preparation of the section on effective horsepower used in this report, and assistance during the tests. Mr. G. Minard very ably handled all problems related to instrumentation.

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1. Sottorf, W., "Experimental Investigations Concerning the Problems of Hydrofoils," (first reported in December 1940), David Taylor Model Basin Translation No. 299 (June 1966).

2. Jones, H.D. and Gerzina, D.M., "Motions and Hull-Induced Bridging Structure Loads for a Small Waterplane Area, Twin-Hull Attack Aircraft Carrier in Waves," (SWATH II), Naval Ship Research and Development Center Report 3819 (August 1973).

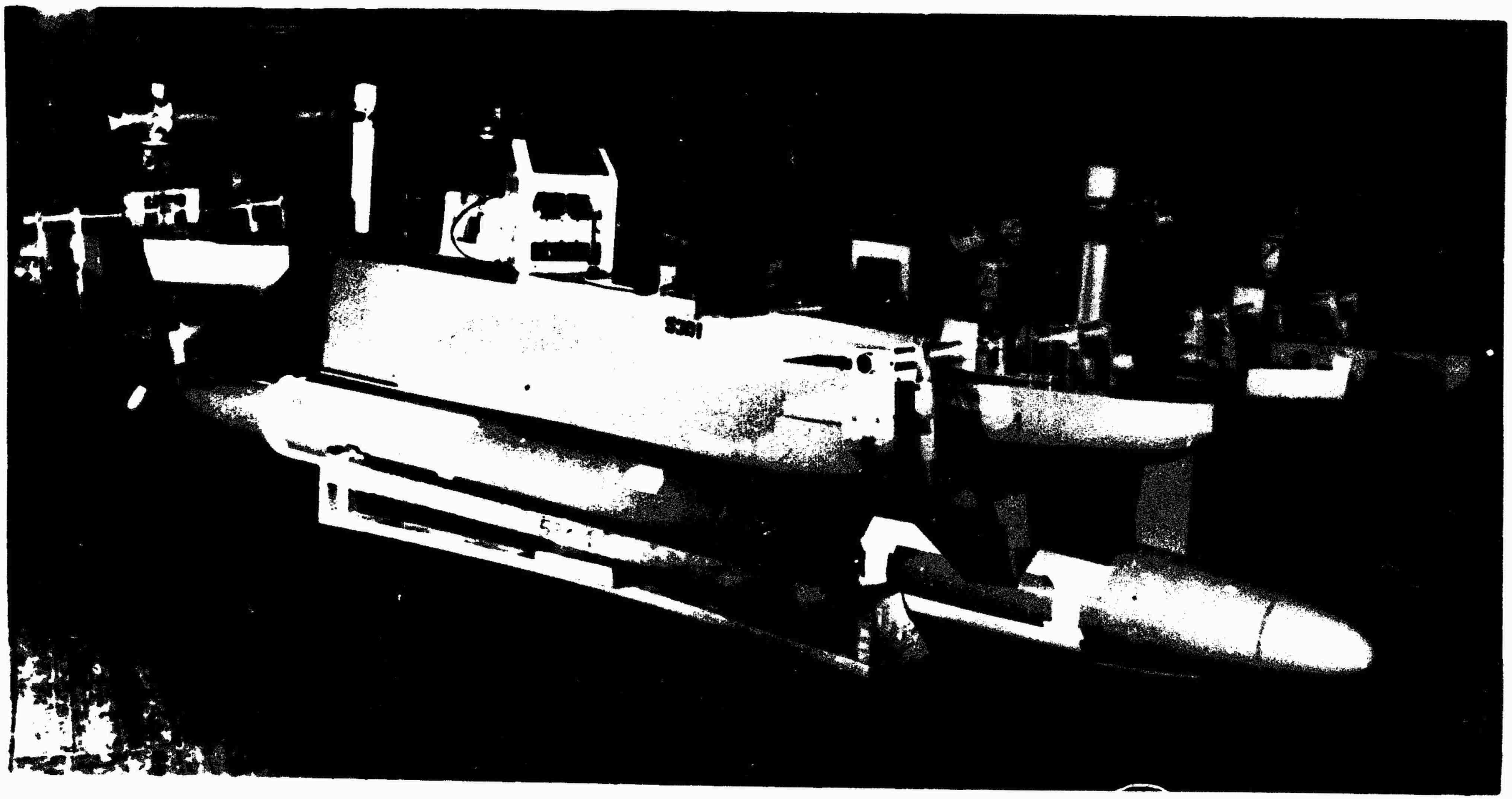


Figure 1 - SWASH Model

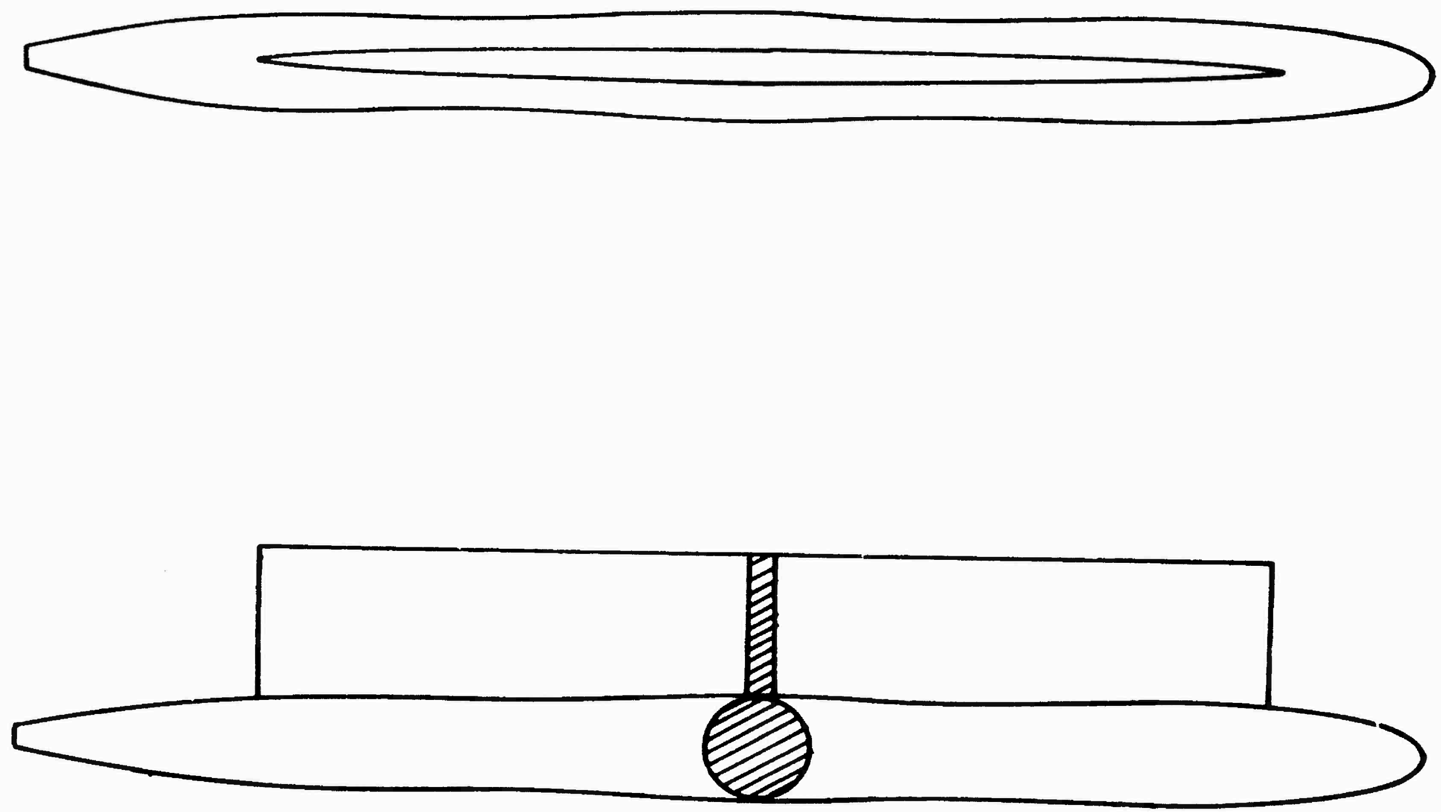


Figure 2 - Abbreviated Lines for SWASH Hull Represented by Model 5301

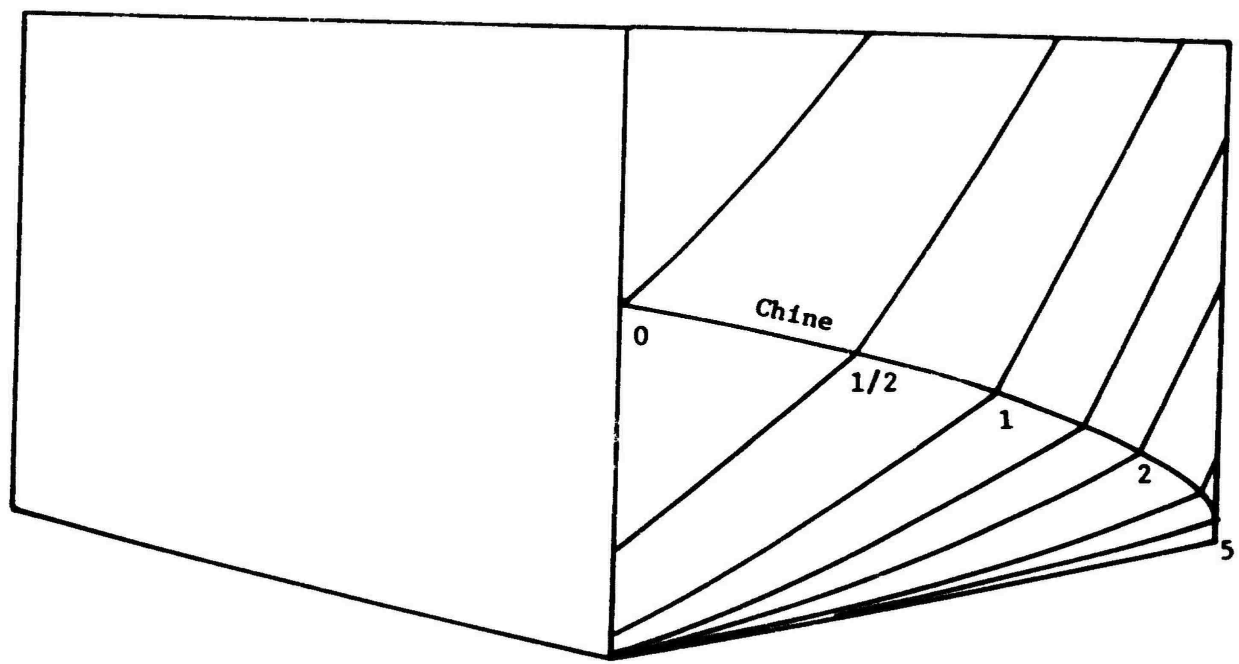


Figure 3 - Body Plan for Planing Float

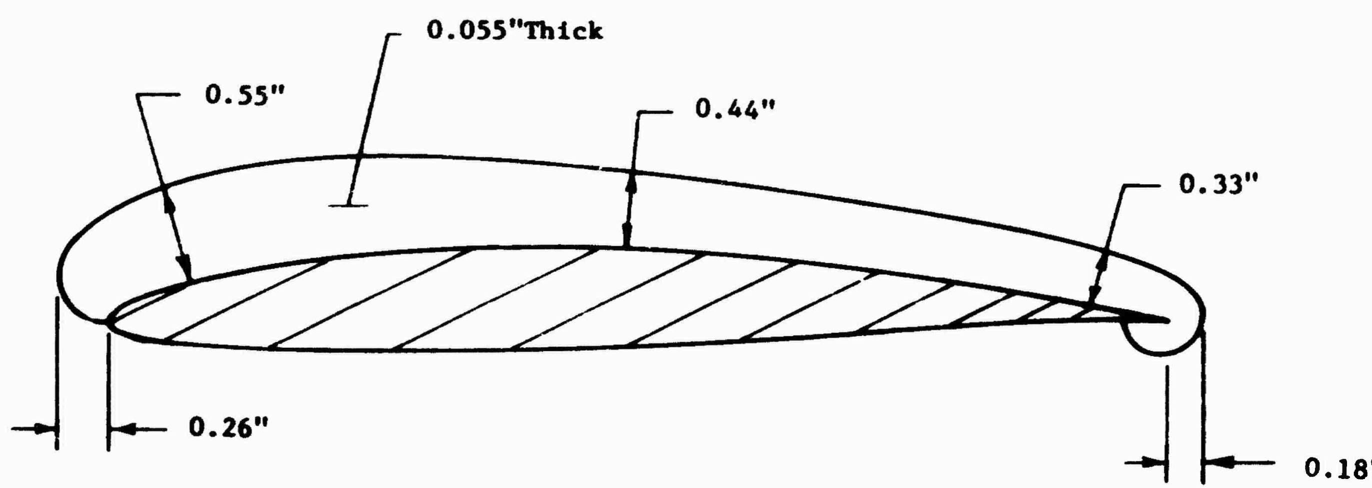


Figure 4 - Hydrofoil Cross-Section with Fence
(NACA 64A010 with a = 1.0 Mean Line for C_1=0.45)

Figure 5 - Dihedral Hydrofoil Assembly

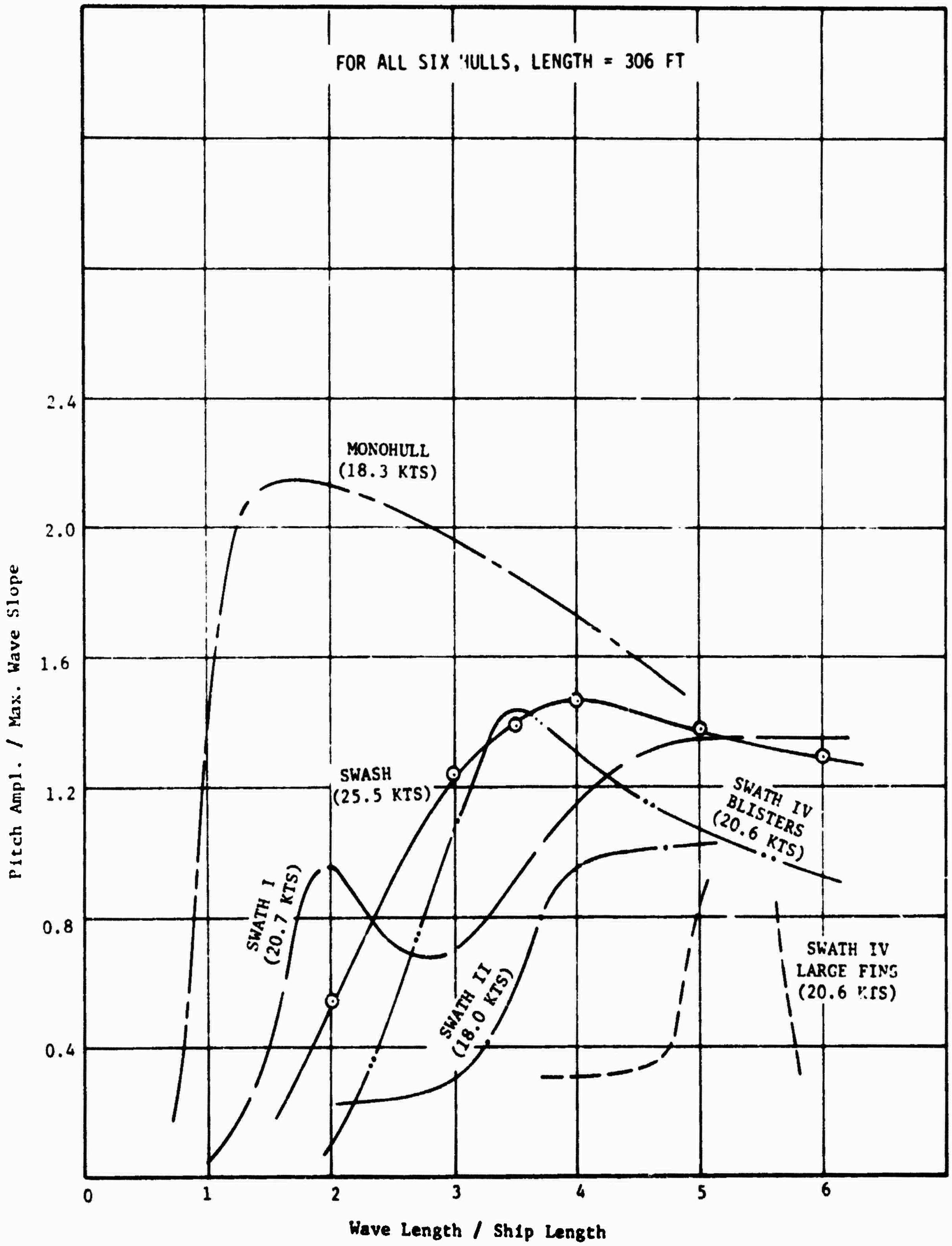


Figure 6 - Comparison of Pitch Transfer Functions Obtained in Head Regular Waves for SWASH, SWATH, and a Conventional Monohull; SWASH Speed = 25.5 Knots

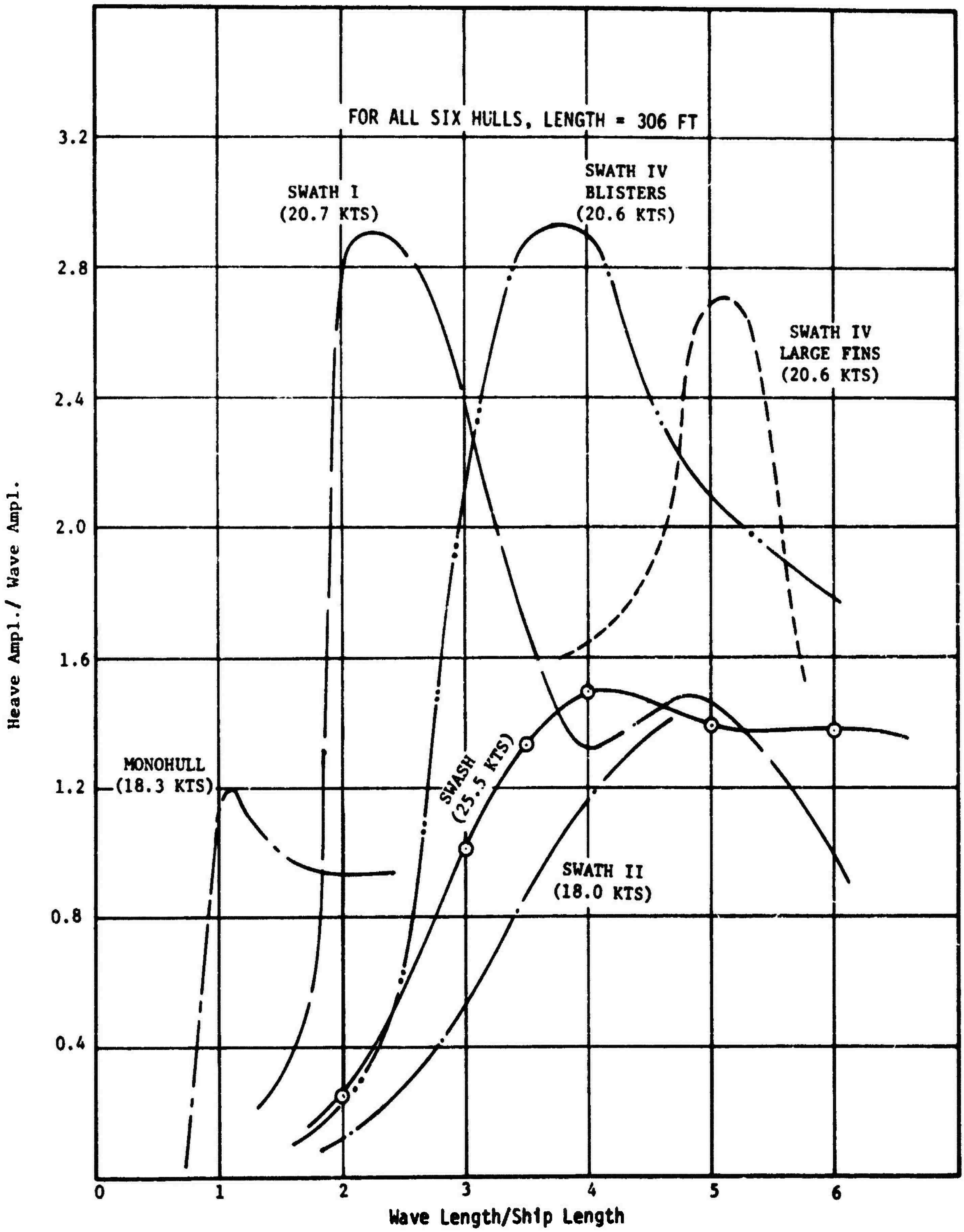


Figure 7 - Comparison of Heave Transfer Functions Obtained in Head Regular Waves for SWASH, SWATH, and a Conventional Monohull; SWASH Speed = 25.5 Knots

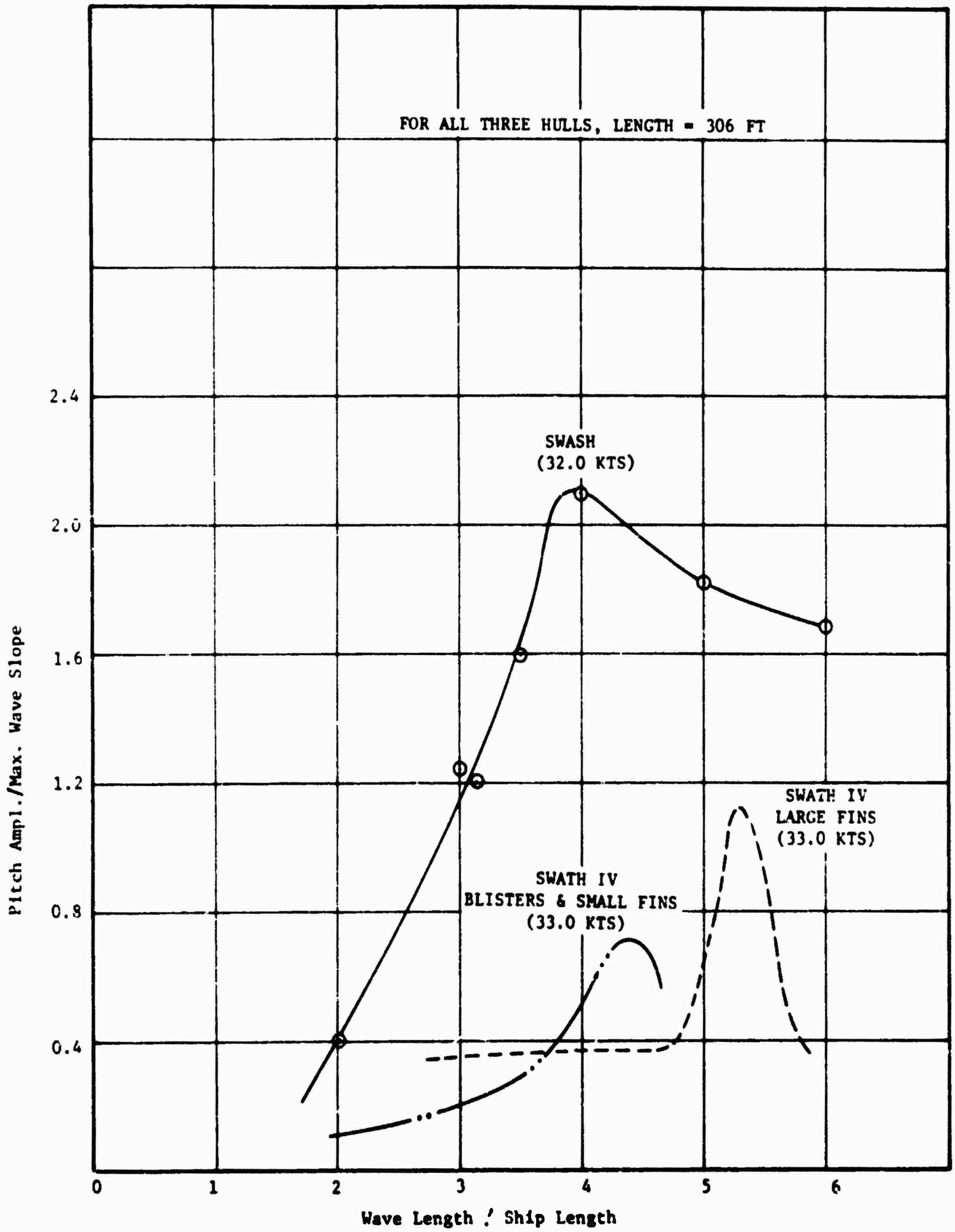


Figure 8 - Comparison of Pitch Transfer Functions Obtained in Head Regular Waves for SWASH and SWATH; SWASH Speed = 32.0 Knots

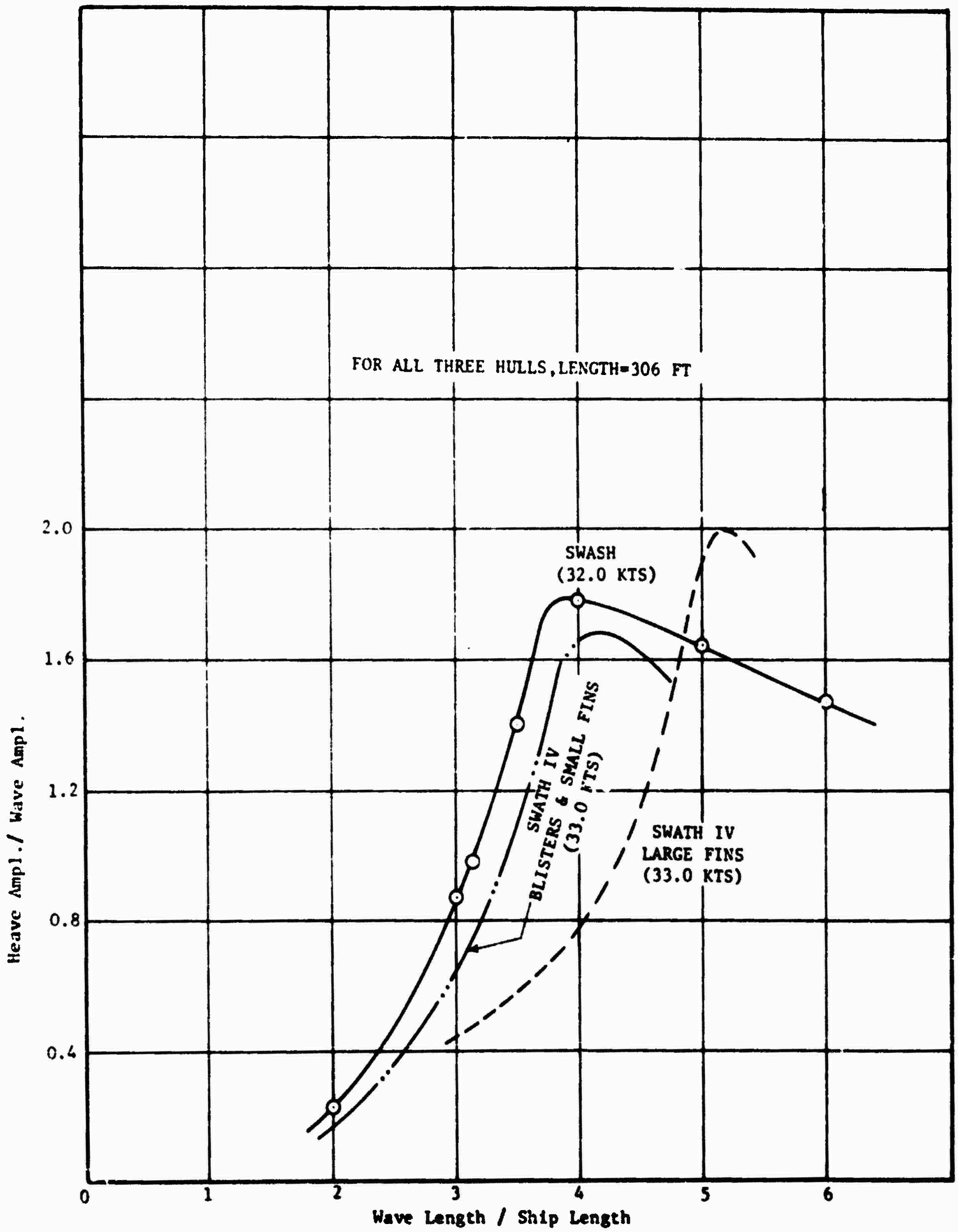


Figure 9 - Comparison of Heave Transfer Functions Obtained in Head Regular Waves for SWASH and SWATH; SWASH Speed = 32.0 Knots

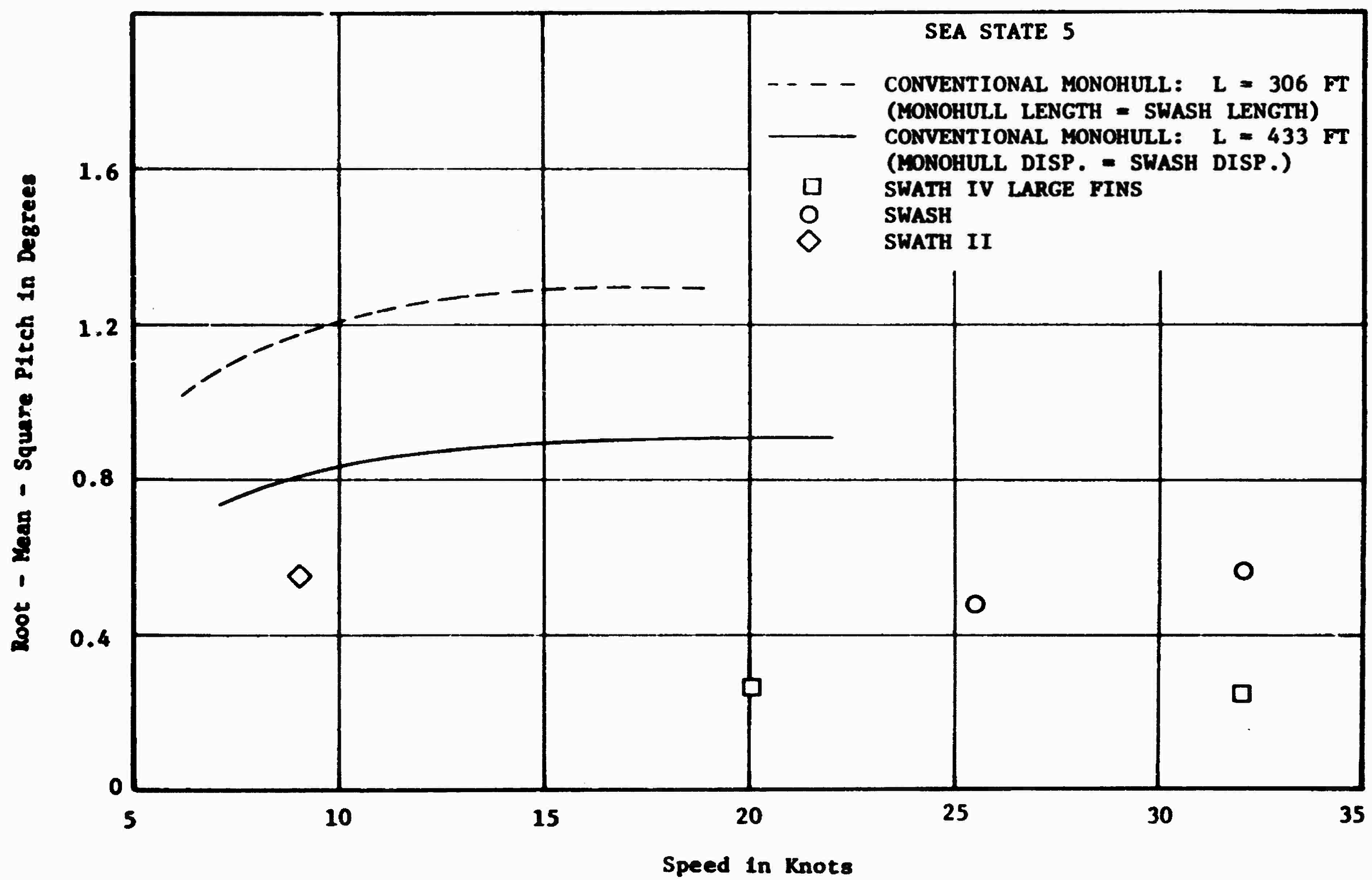


Figure 10 - Comparison of Pitch in a Head Sea State 5 for SWASH, SWATH and a Conventional Monohull

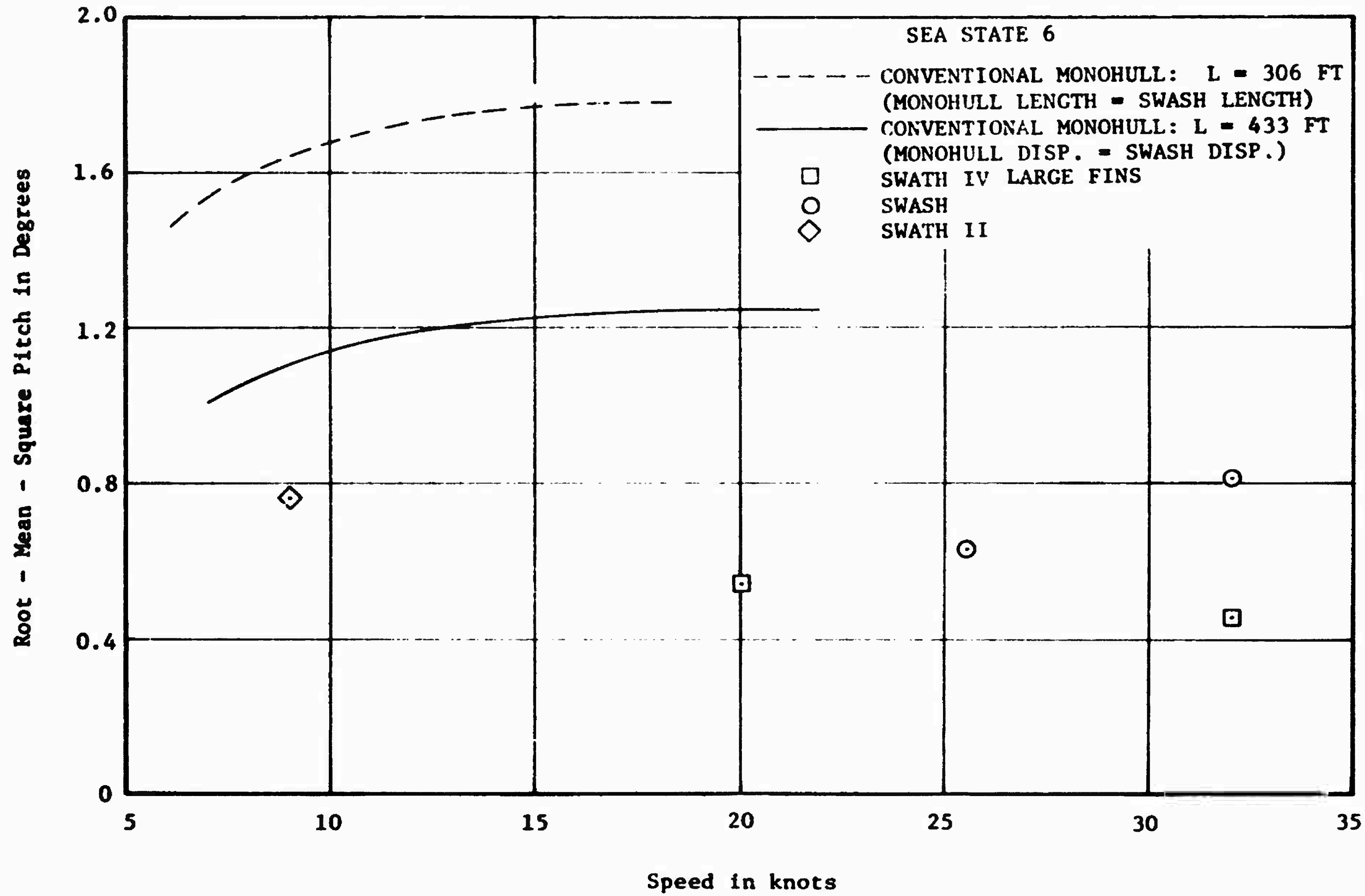


Figure 11 - Comparison of Pitch in a Head Sea State 6 for SWASH, SWATH and a Conventional Monohull

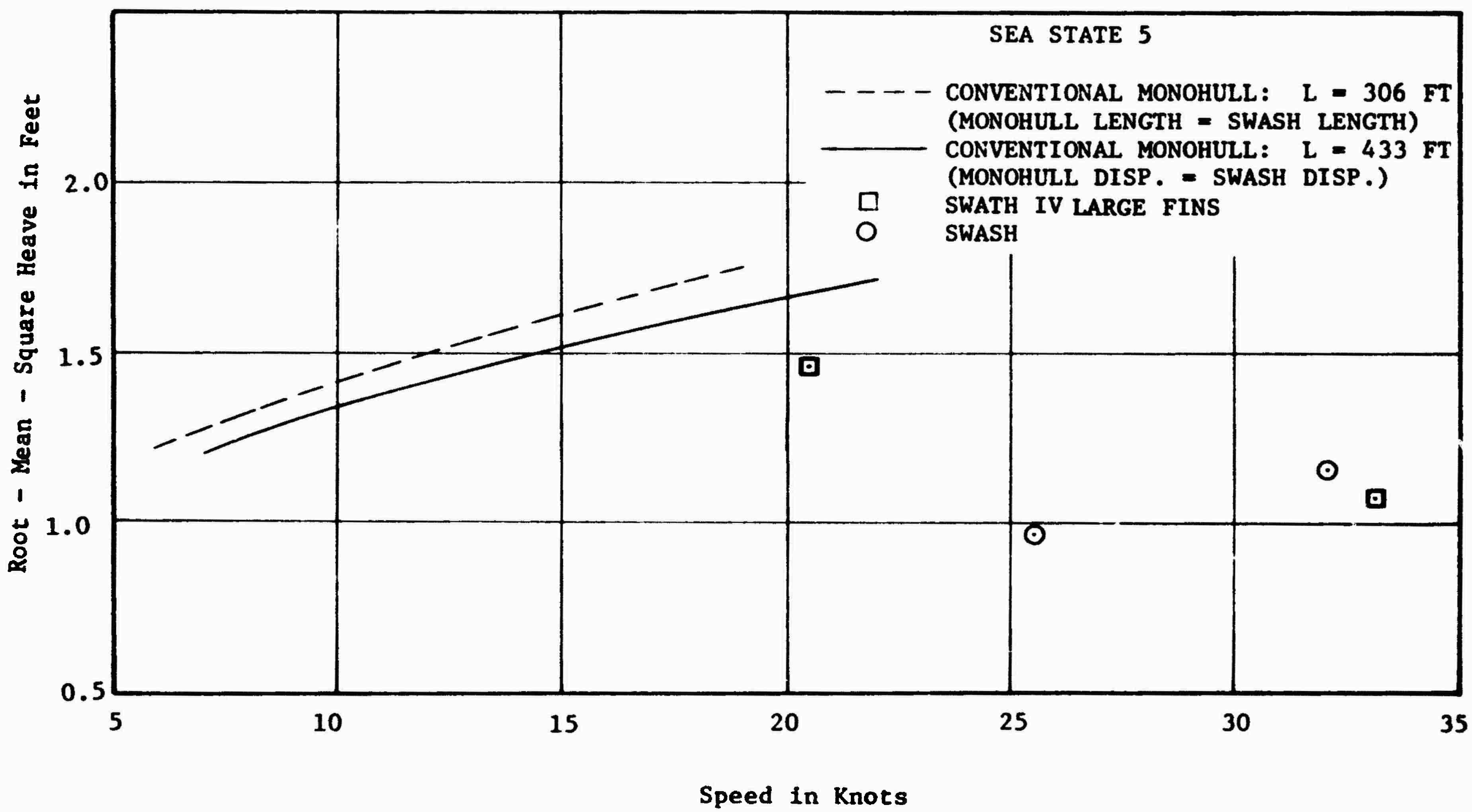


Figure 12 - Comparison of Heave in a Head Sea State 5 for SWASH, SWATH, and a Conventional Monohull

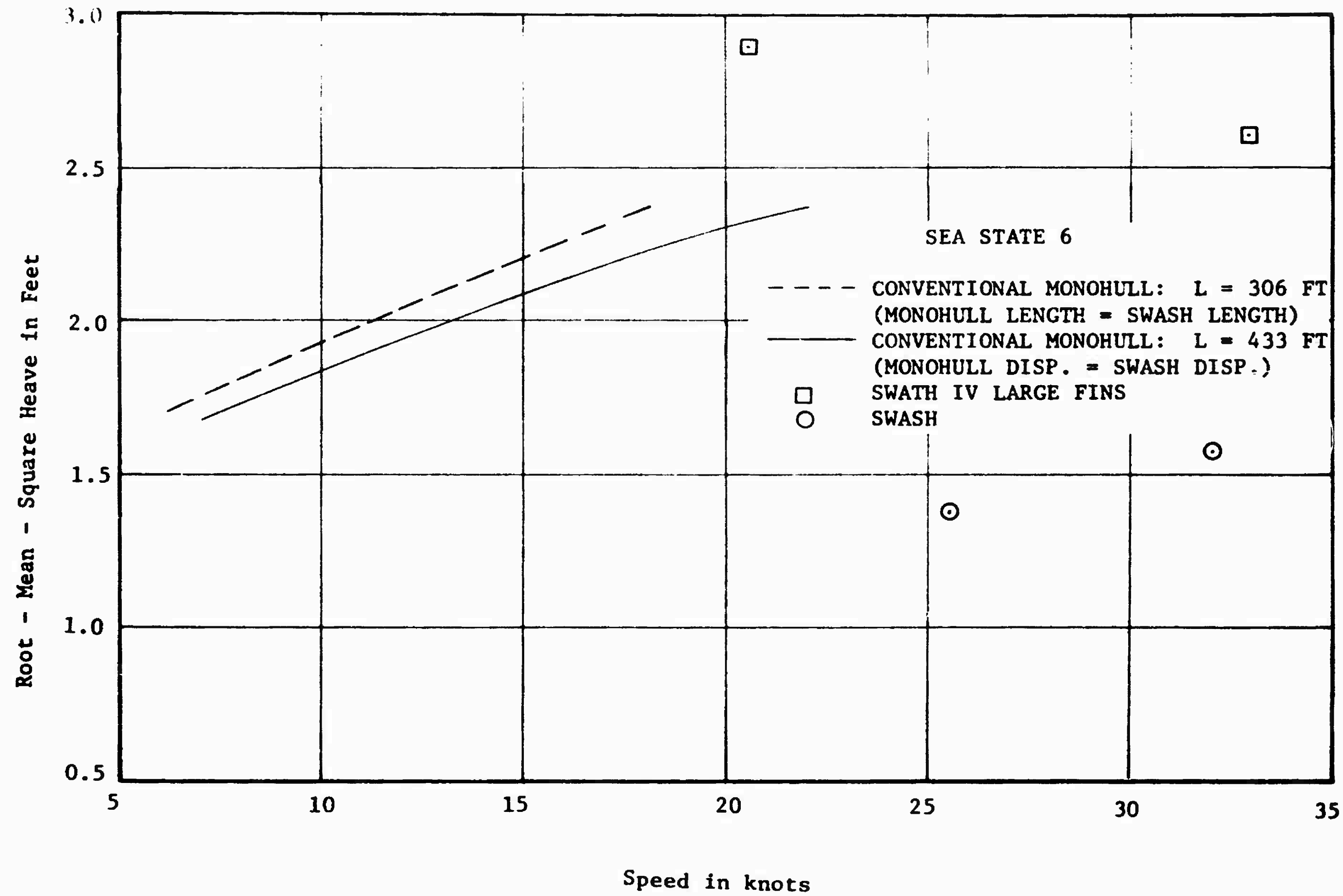


Figure 13 - Comparison of Heave in a Head Sea State 6 for SWASH, SWATH, and a Conventional Monohull

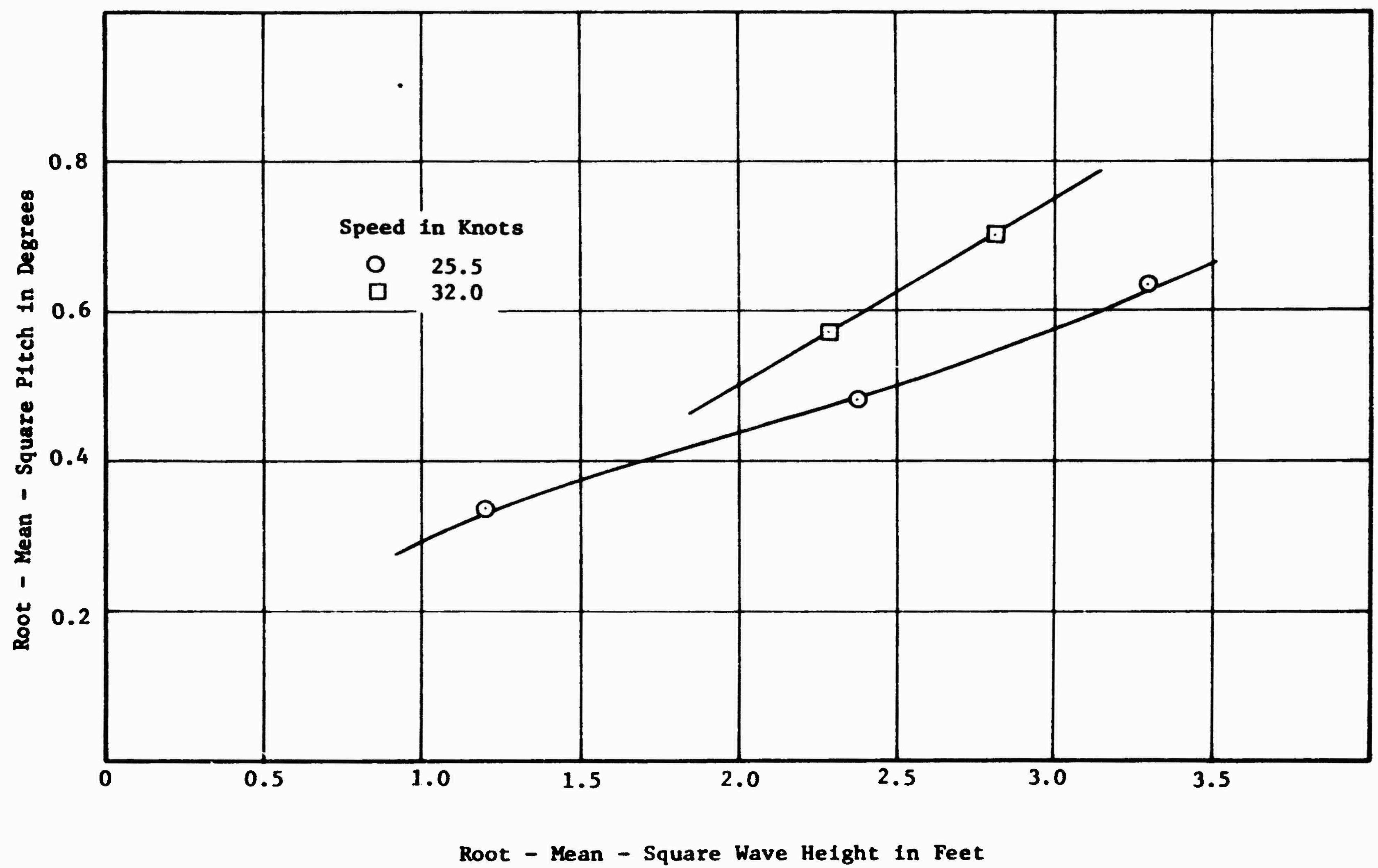


Figure 14 - Pitch versus Wave Height for SWASH

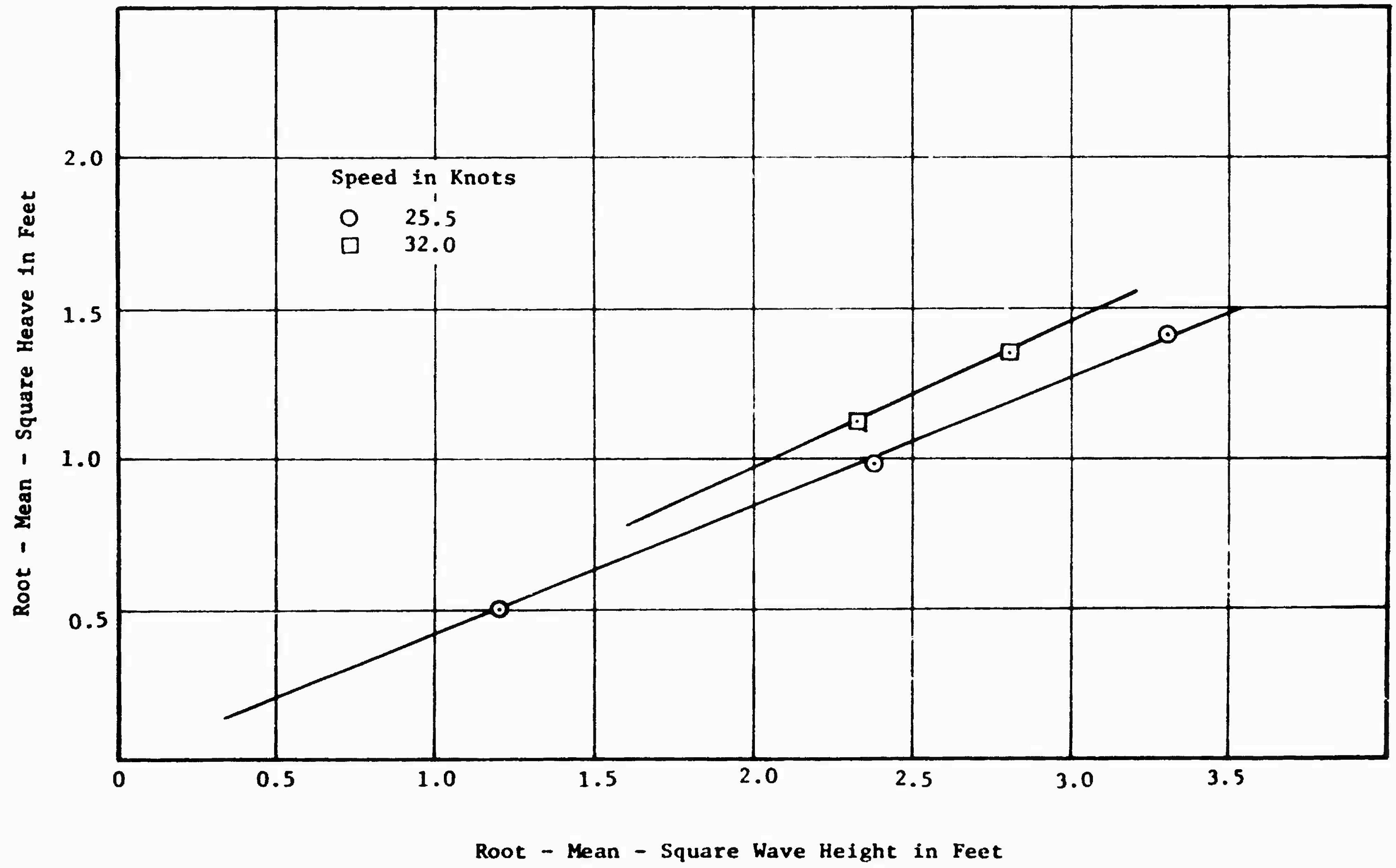


Figure 15 - Heave Versus Wave Height for SWASH

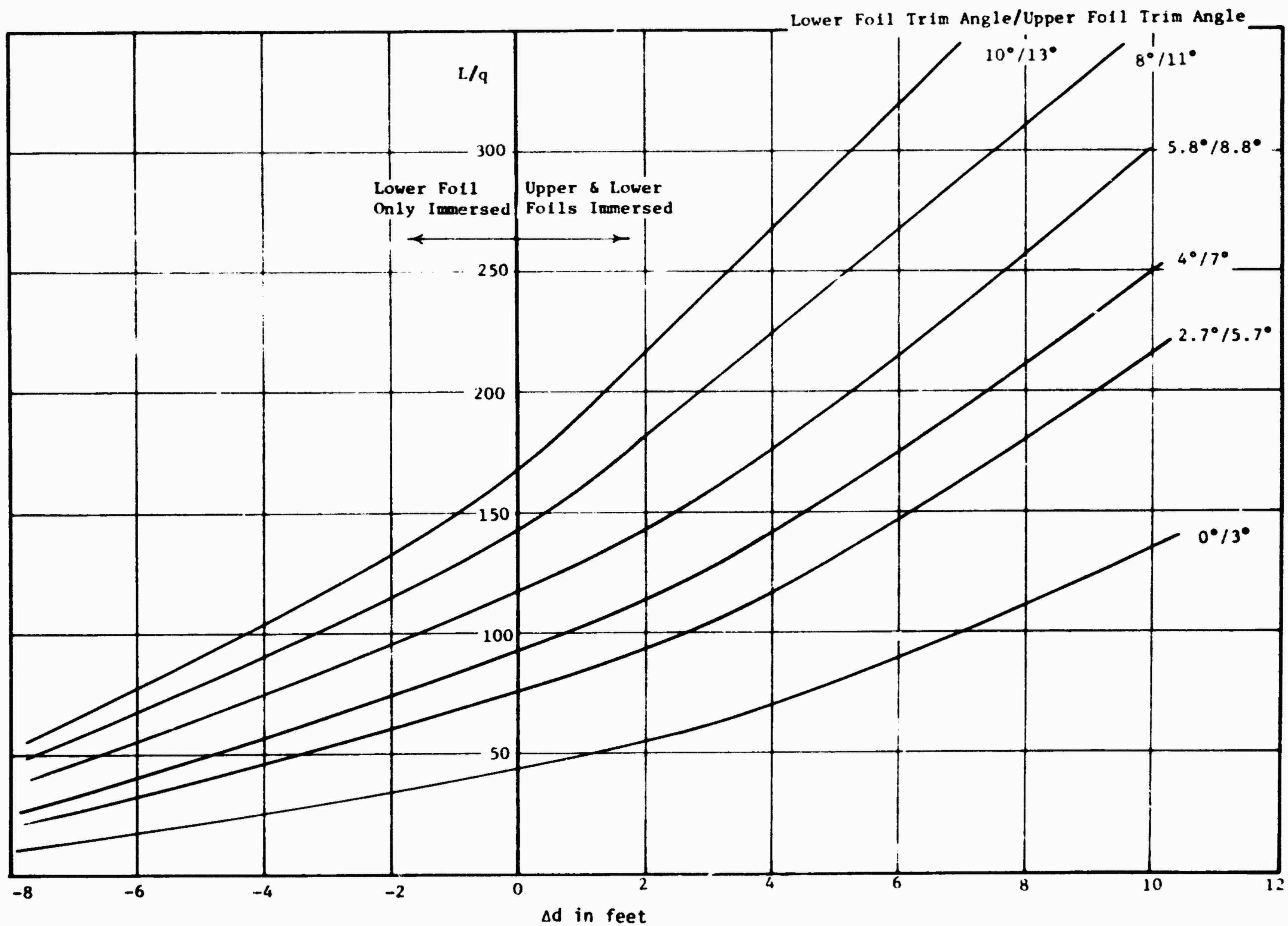


Figure 16 - Lift/Dynamic Pressure versus Immersion Depth for SWASH Foil Unit

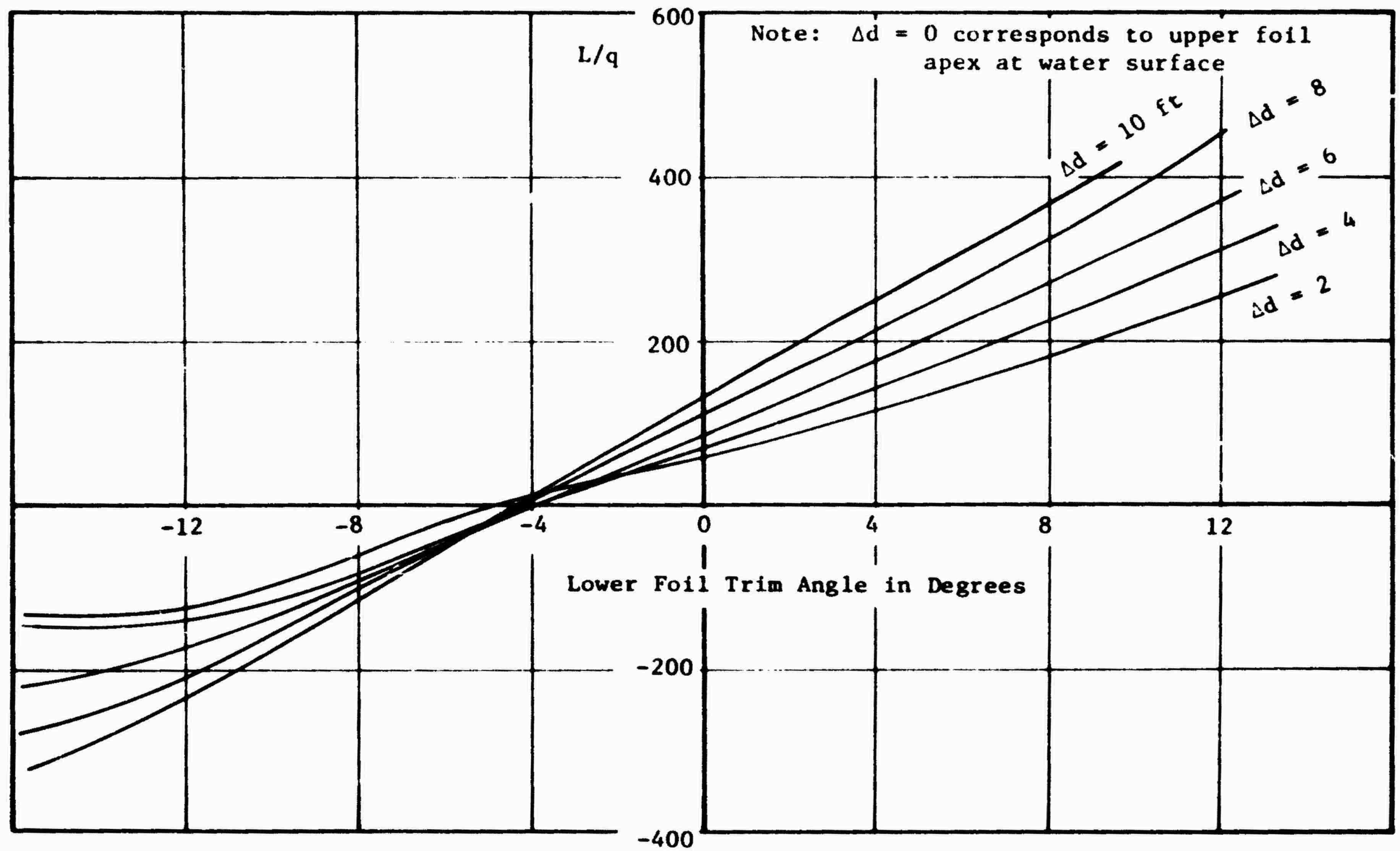


Figure 17 - Lift/Dynamic Pressure versus Trim Angle for SWASH Foil Unit; Immersion of Upper Foil Apex as a Parameter

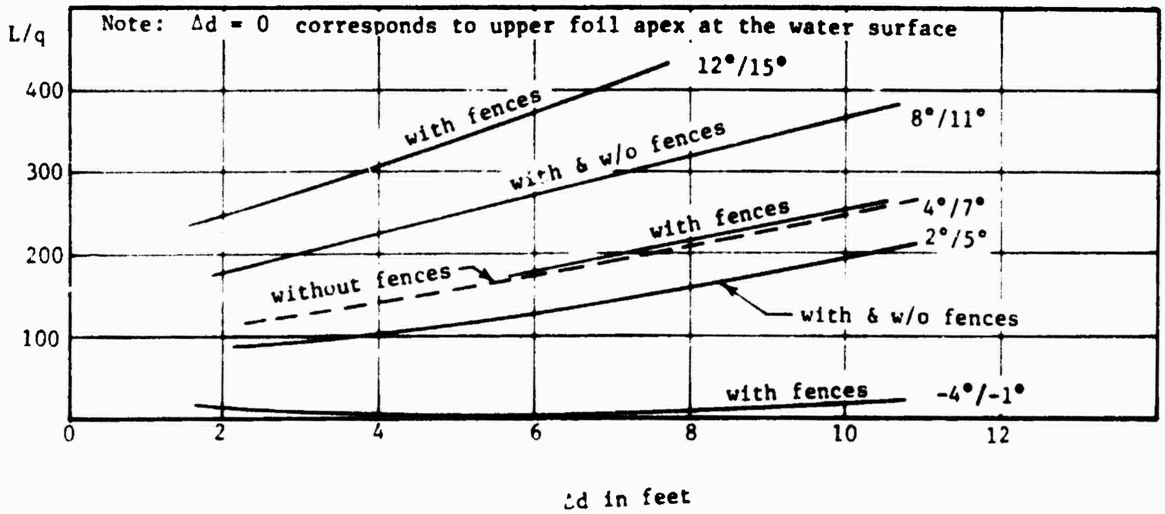


Figure 18- The Effect of Fences on
Lift for the SWASH Foil Unit

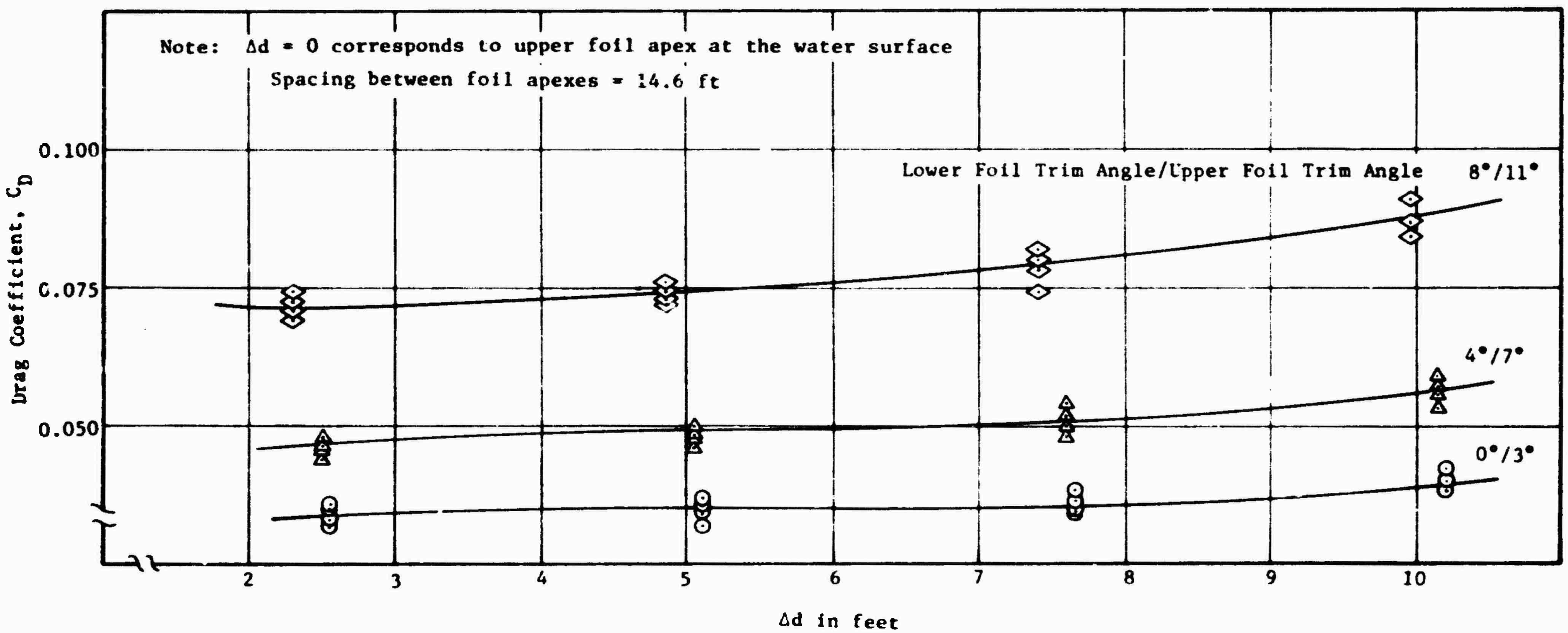


Figure 19 - Drag Coefficient as a Function of Immersion Depth for SWASH Foil Unit

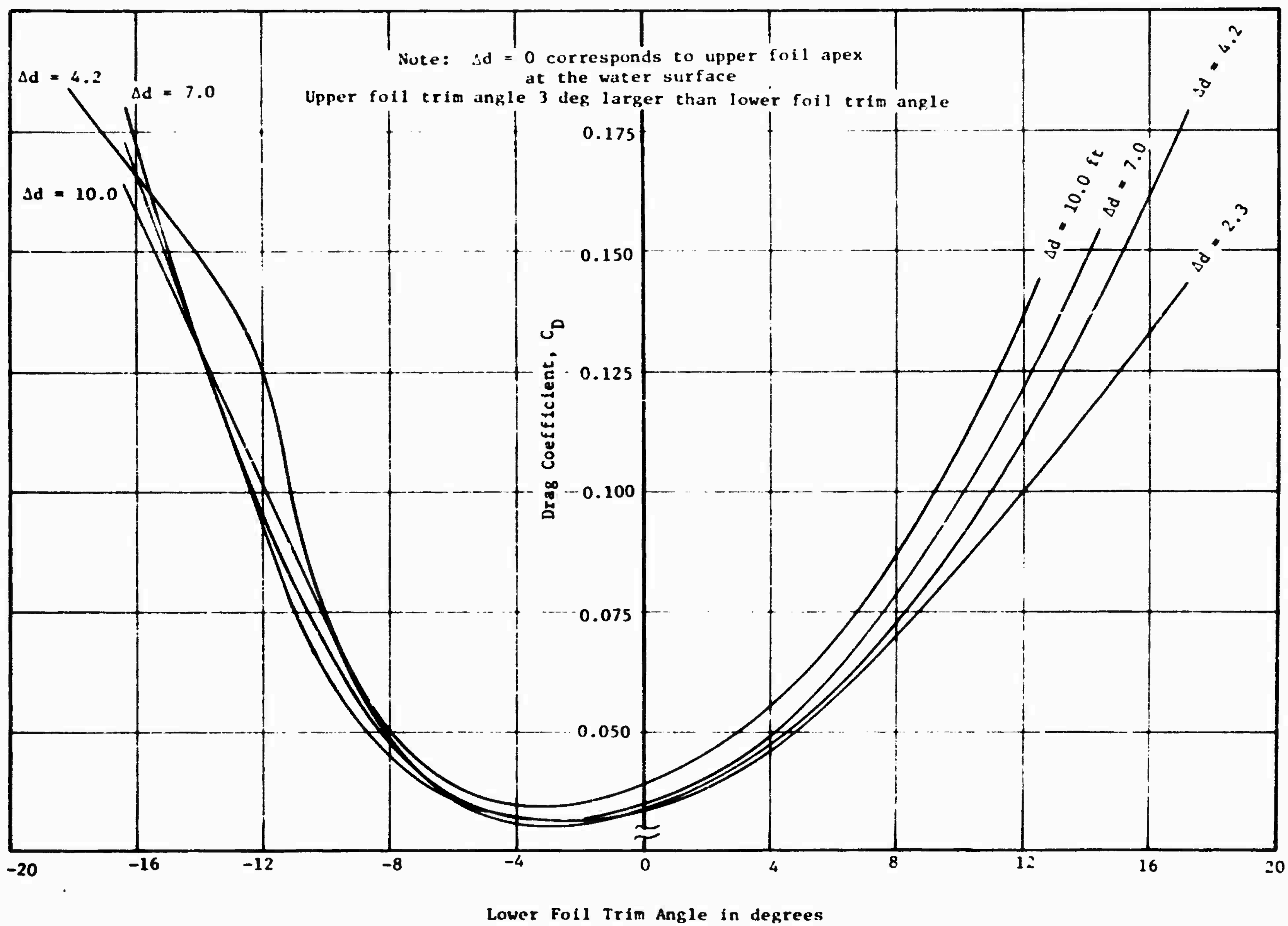


Figure 20- Drag Coefficient as a Function of Trim Angle for SWASH Foil Unit

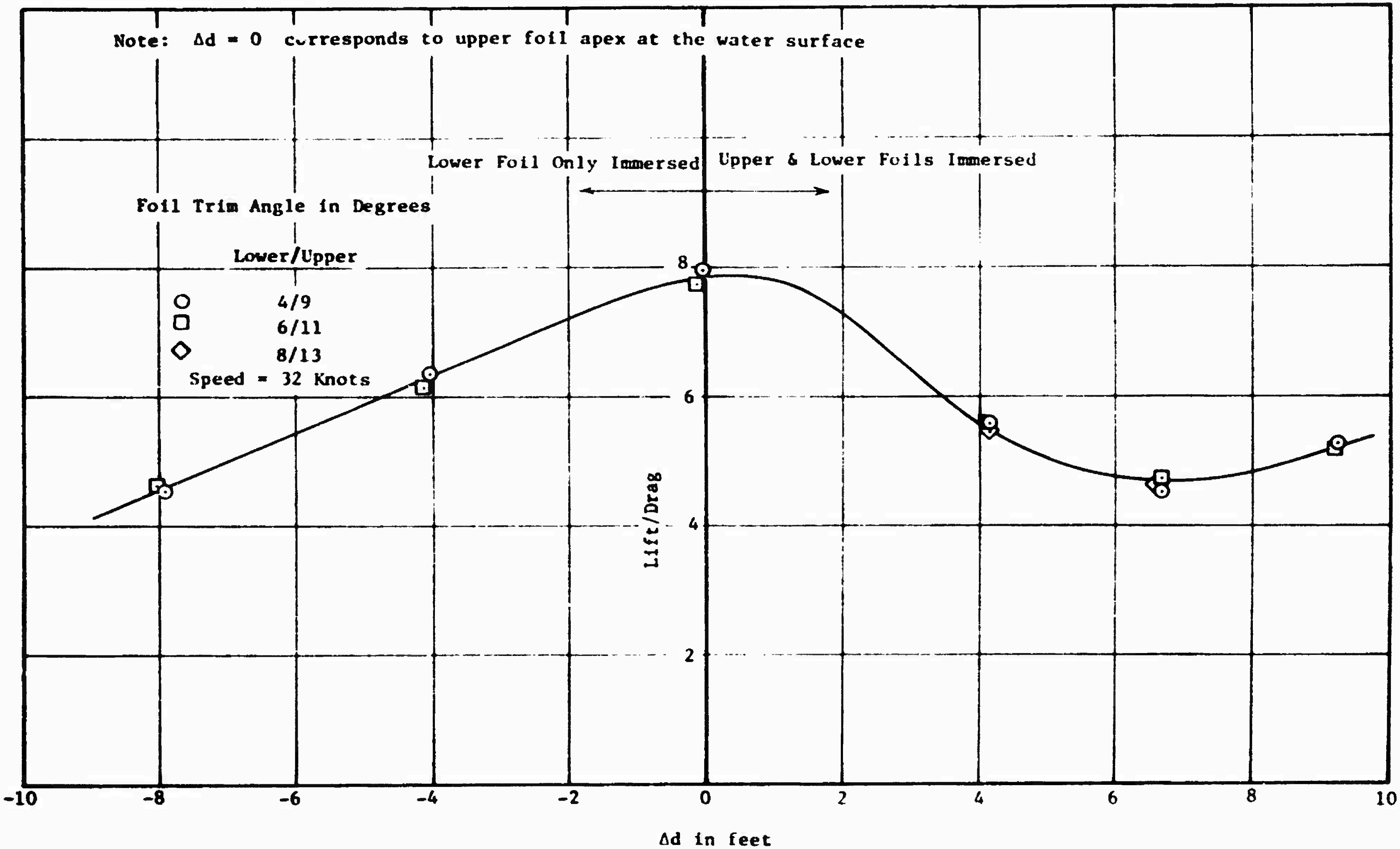
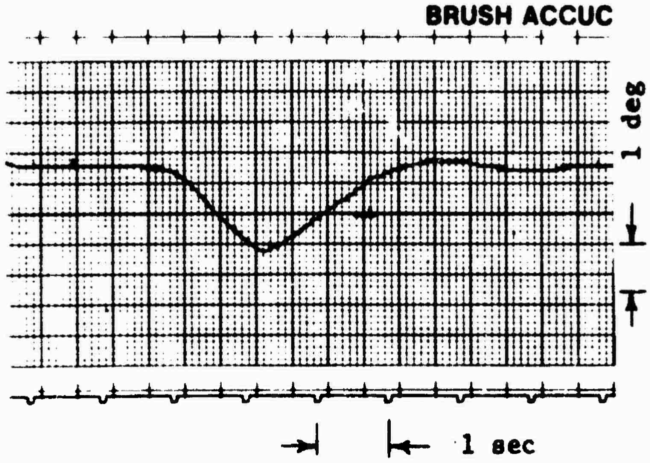
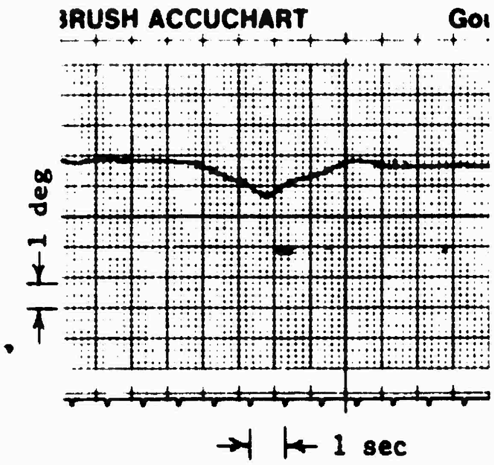


Figure 21 - Variation of Lift-To-Drag Ratio With Immersion Depth for SWASH Foil Unit

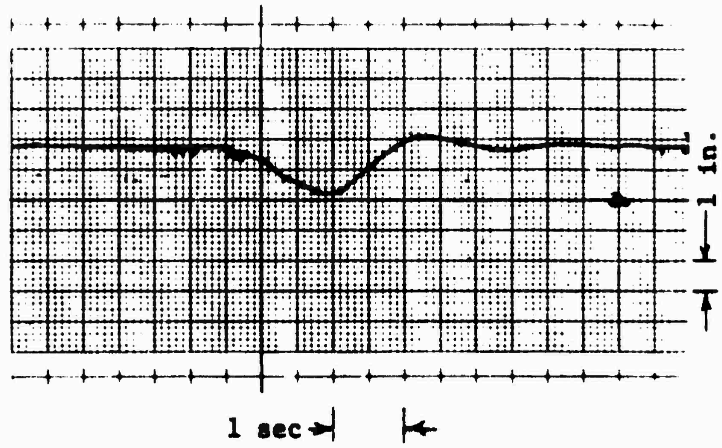
Time Increases



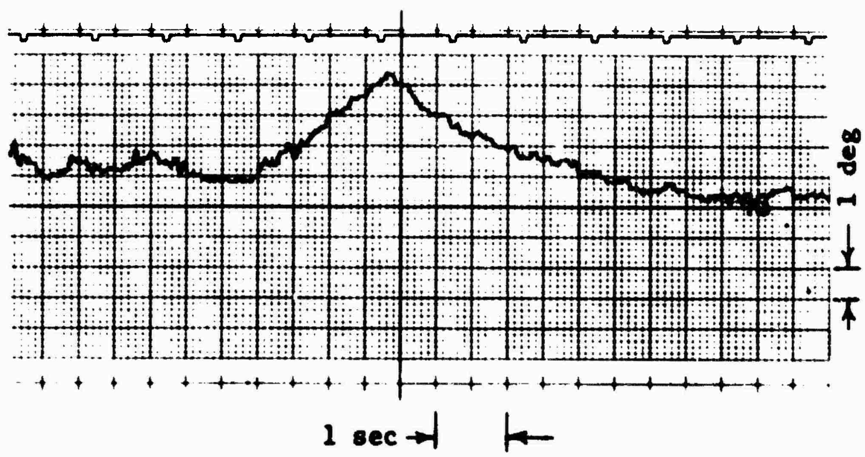
Free Pitch Oscillation, V = 25.5 Knots



Free Pitch Oscillation, V = 32.0 Knots



Free Heave Oscillation, V = 25.5 Knots



Free Roll Oscillation, V = 25.5 Knots

Figure 22- Strip Charts from Free Oscillation Experiments

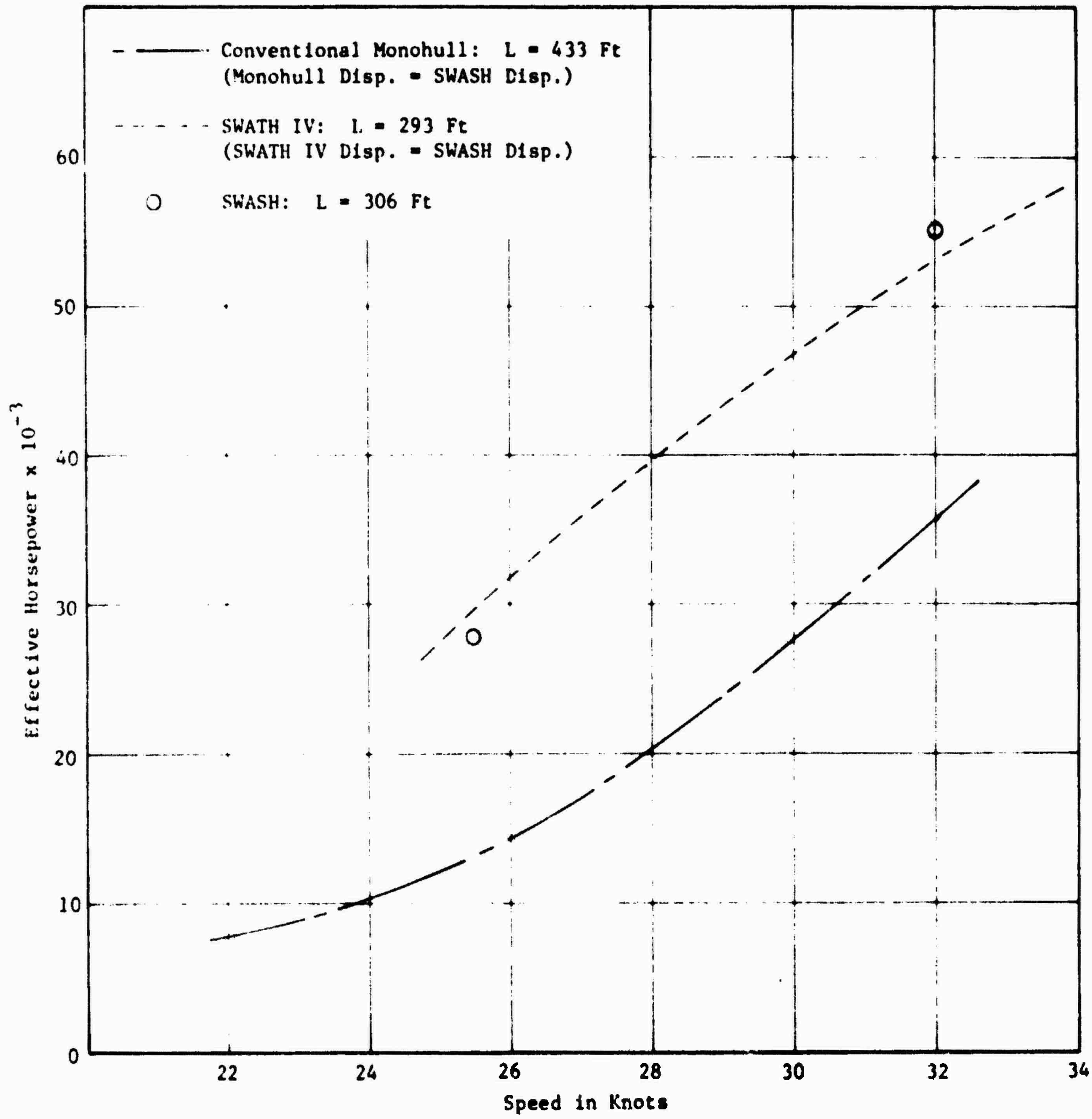


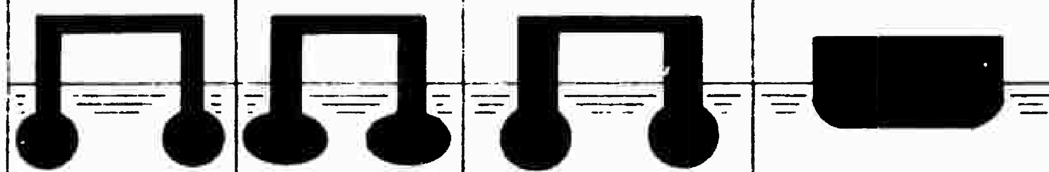
Figure 23- Effective Horsepower for SWASH, SWATH IV and a Conventional Monohull

TABLE 1 - SHIP AND MODEL PARTICULARS FOR SWASH

ITEM	SHIP	MODEL
LENGTH, OVERALL, ft	306.0	15.0
LENGTH, ON WATERLINE, ft	225.0	11.03
BEAM, MAIN HULL, ft	24.2	1.19
BEAM, DECK (NOMINAL), ft	100.0	4.90
HYDROFOIL SPAN, TIP TO TIP (NOMINAL), ft	63.9	3.13
DRAFT, AT 32 KNOTS (APPROXIMATE), ft	38.0	1.86
GROSS WEIGHT	4166 LT SW	1069 LB FW
DISTANCE BETWEEN FWD AND AFT FOILS, ft	200.0	9.8
TRANSVERSE DISTANCE BETWEEN ℄ OF PORT AND STARBOARD FOILS, ft	92.0	4.5
LONGITUDINAL CENTER OF GRAVITY (LCG), AFT OF FP, ft	150.45	7.38
LONGITUDINAL RADIUS OF GYRATION	0.26 LOA	0.26 LOA
LATERAL RADIUS OF GYRATION	0.11 LOA	0.11 LOA
VERTICAL CENTER OF GRAVITY ($\overline{KG}$), ft	36.94	1.81
WATERPLANE AREA, ft^2	930.0	2.23
LONGITUDINAL WATERPLANE MOMENT OF INERTIA, ft^4	2.23×10^6	12.88
NATURAL HEAVE PERIOD*, sec	10.4	2.3
NATURAL ROLL PERIOD*, sec	12.2	2.7
SCALE RATIO		1:20.4

* BECAUSE OF HEAVY DAMPING THESE VALUES WERE OBTAINED FROM FORCED OSCILLATION TESTS, AND ARE APPROXIMATE.

TABLE 2- PRINCIPAL CHARACTERISTICS OF THE SWATH SHIPS AND CONVENTIONAL MONOHULL



	SWATH I	SWATH II	SWATH IV		MONOHULL	
			EQUIV. LENGTH	EQUIV. DISPL.	EQUIV. LENGTH	EQUIV. DISPL.
Length (LBP) in Feet	306	306	306	293	306	433
Displacement in Tons	4,789	2,356	5,141	4,166	1,346	4,166
Beam(Each Hull) in Feet	18.1	10.9	19.1	18.3	31.7	45.0
Hull Spacing in Feet*	92.9	75.2	60.6	58.1	-------	----------
Draft in Feet	23.5	25.0	34.0	28.5	10.4	15.6

*Distance between closest points